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# HUMAN RADIATION EXPOSURES RELATED TO NUCLEAR WEAPONS INDUSTRIES

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SECTION I

INTRODUCTION

Little accurate information has generally been received by the public concerning radiation exposures or radioactivity releases from nuclear weapons industries and this has caused uncertainty about their potential health risks to people. This uncertainty, coupled with public statements of opposing legal and scientific advocates, has led to much concern and litigation that are often difficult to justify on the basis of scientific facts. The objectives of this report are to summarize events that led to accidental or planned releases of radioactivity into the environment from nuclear weapons industries, to estimate the levels of radiation exposures and health risks to people who received or may receive irradiation, to review important scientific aspects of litigations that resulted from these radiation exposures, and to use this experience in recommending better means of evaluating and managing the effects of similar accidents should they occur in the future.

To meet these objectives in a manner useful to people, either with scientific or nonscientific backgrounds, Section 1 describes some historical aspects and the scope of concerns over radiation exposures related to nuclear weapons industries. Section 2 provides a general discussion of the dosimetry and health effects of ionizing radiation and mathematical methods for estimating the risks. Section 3 describes epidemiologic and laboratory studies that are now being done on radiation workers, medical patients, atomic bomb survivors, and laboratory animals. Sections 4 and 5 discuss the nuclear weapons test programs at the Nevada and Pacific test sites, with descriptions of the events, levels of radioactivity released to the environment, radiation exposures to people, and major aspects of the related litigations. Section 6 describes similar aspects of radioactivity releases from the Rocky Flats nuclear weapons facility and includes information on exposures to workers and people living nearby. Section 7 provides a summary of accidents that have occurred in transporting nuclear weapons. It mainly focuses on accidents at Palomares, Spain and Thule, Greenland, since most other accidents occurred at sea or on land without resulting in significant radiation exposures to people. Section 8 summarizes the report and discusses how our previous experiences can be used to improve scientific research and the management of future radiation accidents.

The concept of building atomic weapons arose soon after the discovery of uranium fission in 1938 by Otto Hahn and Fritz Strassman (Hewlett and Anderson 1962). Their studies demonstrated that nuclear fission occurred when uranium was bombarded with neutrons and this led to the release of part of the enormous energy that holds the nucleus together, and more neutrons. Scientists around the world quickly recognized the possibility of creating a self-sustaining chain reaction in uranium that would release large amounts of energy with explosive force. This concept launched a great scientific and engineering effort beginning in 1940 to build an atomic bomb because of its potential importance in World War II. However, the theory of a self-sustaining nuclear fission reaction was not demonstrated experimentally until December, 1942. This was accomplished by Enrico Fermi and his co-workers using a uranium and graphite pile built in a room beneath Stagg Field in Chicago, Illinois. The early efforts to build atomic weapons were organized into the Manhattan Engineer District in August, 1942, Figure I-1. This led to establishing the first U. S. nuclear weapons laboratories at Los Alamos, New Mexico and Oak Ridge, Tennessee in 1943. Practical weapons designs were then produced within three years. On August 6, 1945, the United States armed forces detonated a nuclear weapon (code name "Little Boy") over the Japanese city of Hiroshima. Three days later, a second nuclear weapon (code name "Fat Man") was detonated over Nagasaki, Japan. Both cities were destroyed and Japan surrendered shortly thereafter, ending World War II.

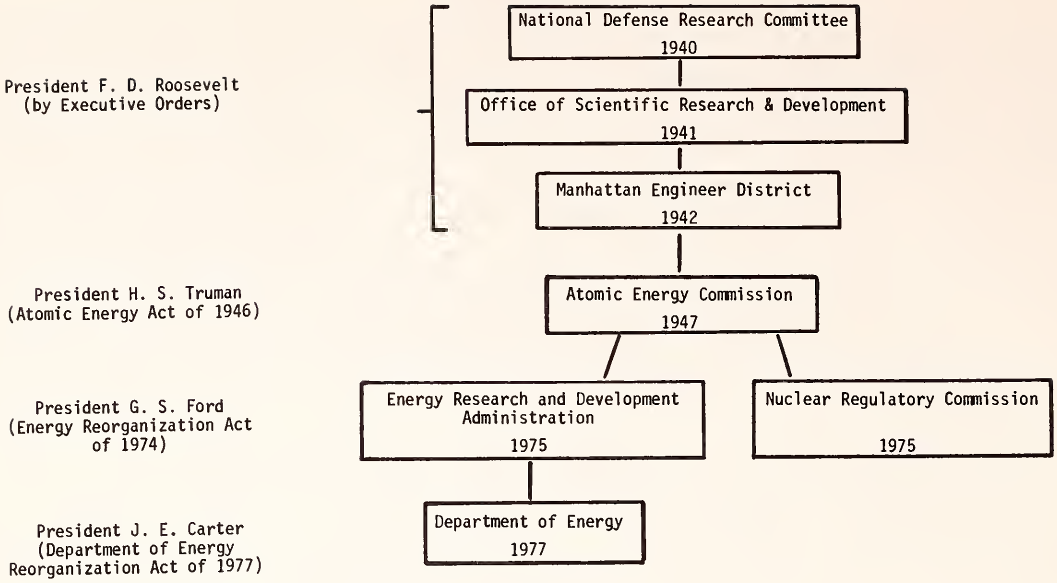


Figure I-1. Historical sequence of government organizations responsible for development of the United States nuclear weapons program.

After World War II, the Atomic Energy Act, signed by President Truman on August 1, 1946, transferred the Army's Manhattan Engineer District programs to the Atomic Energy Commission. The Atomic Energy Act of 1954, signed by President Eisenhower, made possible greater participation by private industry and cooperation with other countries in developing peaceful uses of nuclear energy. The Atomic Energy Acts of 1946 and 1954 contain the overall authority given to the Atomic Energy Commission to develop nuclear weapons and conduct weapons tests (U.S. Congress 1954).

"Sec. 91 Authority - The Commission is authorized to:

(1) Conduct experiments and do research and development work in the military application of atomic energy; and

(2) Engage in the production of atomic weapons or atomic weapon parts, except that such activities shall be carried on only to the extent that the express consent and direction of the President of the United States has been obtained, which consent and direction shall be obtained at least once each year."

Possible terms for its consent are described in provisions of the Federal Tort Claims Act. The two Atomic Energy Acts made the decisions and actions necessary to carry out the nuclear weapons program high-level policy actions that are discretionary functions. The authority of the Atomic Energy Commission was subsequently transferred to the Energy Research and Development Agency through the Energy Reorganization Act of 1974 and then to the Department of Energy through the Department of Energy Reorganization Act of 1977.

As the nuclear weapons program developed, new technologies were needed to handle the large amounts of radioactive materials that resulted. Some of these materials were waste products, but others became components of nuclear weapons. During the last 40 years the weapons have been stored for long periods of time, transported by land, sea and air, remanufactured, and tested.

Accidental and intended releases of radioactivity and radiation from these operations have led to exposures of many people. However, because health experts were aware of the risks due to ionizing radiation from the beginning of the nuclear weapons program (Taylor 1970), appropriate protective measures were taken and few people are likely to have been injured by radiation from the weapons related industries. Although many radiation injury claims are now being litigated in courts throughout the United States, this is probably not due to a lack of scientific knowledge about radiation health effects, but is more likely the result of a myriad of complex scientific, legal, and social concerns. Thus, it becomes necessary for the opposing sides in such a litigation to debate complex technical and medical questions that often involve testimony of experts on subjects that are unfamiliar to nonscientists.

Radiation exposures may result from sources of penetrating radiation outside of the body or from internally deposited radionuclides. Important sources of external radiation related to the nuclear weapons program have been nuclear weapons detonations, radioactive fallout, operating nuclear reactors, and nuclear fuel reprocessing. The most important internal depositions of radioactivity have occurred in underground uranium miners and in workers handling nuclear fission products, uranium, and transuranium radionuclides. Members of the public have also been exposed to radiation from nuclear weapons test fallout and from radionuclides that were released to the environment from accidents involving nuclear weapons, from facilities that produce nuclear weapons components, and from nuclear reactors.

The types of health effects caused by radiation and their probabilities of occurring depend upon the total doses and dose rates to critical body tissues (Glasstone and Dolan 1977, National Research Council 1980). Exposures to large areas of the body that result in doses exceeding a few hundred rad delivered within hours may cause massive tissue destruction, loss of organ function, and even death when the injury involves vital body functions. These injuries normally become observable within weeks, but in rare cases they may not become observable until more than one year after the radiation exposure. Because these exposures and effects are closely related in time, they are easy to detect in radiation exposed individuals and seldom are the subject of litigation.

Radiation exposures that occur at rates of only a few rad per year do not result in obvious early effects, but they may increase an individual's risk of developing cancer later in life or of transmitting genetic mutations to subsequent generations. These risks are usually stated in terms of the probabilities that the health effects may occur, and, because of their low frequencies of occurrence, can only be demonstrated by studies of disease incidence in large populations. The late effects of exposures to ionizing radiations are not different from diseases normally expected in people and many years may pass before they occur. Because the presence or absence of radiation injuries caused by low level exposures is difficult to demonstrate the related health concerns are frequent subjects of litigation.

At least three types of litigation have arisen from actual or potential radiation exposures of people related to the nuclear weapons program. These are worker compensation claims, personal injury claims from members of the public, and property loss claims from people who own land near sites where nuclear weapons components were being developed or tested. Worker compensation claims have generally stemmed from cancers that developed in older workers and were thought to have arisen from previous radiation exposures. Because these types of claims are numerous and involve personal information, they will not be discussed individually in this report. However, some general aspects of these litigations will be described to provide insight into the ways in which health specialists, attorneys, and members of the public have evaluated radiation exposure risks.

Currently, the most widely publicized radiation injury litigations involve several hundred people who were residents of Utah between 1950 and 1960 and were exposed to fallout from nuclear weapons detonated at the Nevada Test Site. They received external radiation from passing fallout

clouds and contamination on ground surfaces, and internally deposited radioactivity from ingested and inhaled fallout. Some people have developed different types of cancers and have alleged that the cancers were caused by their previous radiation exposures. The defendant in these litigations is the United States Government.

Two major litigations involving alleged losses of property value or unrestricted use of private property are now pending in U.S. courts. The first will be referred to as the Rocky Flats Land Owners' Litigation, in which people and corporations who own land adjacent to the Rocky Flats facility near Denver, CO, have claimed that they incurred losses of property value and use because of the presence of plutonium released from the plant site. The defendants in this litigation are the U.S. Government, DOW Chemical Company, and Rockwell International Corporation. A second series of litigations is related to nuclear weapons testing at Pacific test sites in the Marshall Islands, Johnston Island, and Christmas Island. Nuclear weapons testing began there in 1946 and continued through 1962. During the tests, people living on the islands were moved to other areas with the intention that they would be returned as soon as conditions permitted. Because radiation risks for people who would be living in some areas of the islands have not declined as quickly as originally anticipated, there has been substantial delay in permanently returning people to their homes. When this will occur is still unclear and the delay has stimulated legal actions in behalf of the displaced individuals.

In an attempt to reduce public concern over minor environmental radiation exposures and to provide a more scientific basis for litigation, the U.S. Congress passed legislation in 1982 asking the National Institutes of Health to formulate numerical tables relating the levels of radiation exposure to subsequent health risks for people of different ages (Orphan Drug Act 1983). These tables are intended for use in evaluating the likelihood that cancers occurring in people could have been caused by a previous radiation exposure. When these tables are completed and accepted by health specialists, attorneys, and the public, important gains may be achieved in reducing the number and cost of radiation-related litigations. However, producing these tables is likely to be a difficult task, as will be described in later sections of this report.

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## SECTION II

## RADIATION DOSIMETRY AND HEALTH EFFECTS

Although man has always lived in an environment with ionizing radiation as part of the natural background, its dangers did not become apparent until people attempted to control and use radiation by producing ever larger and more concentrated sources. Information on its harmful effects began to develop soon after the discovery of X-rays by Roentgen in 1895 and of natural radioactivity by Becquerel in 1896 (Taylor 1970, 1979, 1979a). The first health effects were noticed in overexposed skin which became red and blistered within hours or days of the exposure. By 1902, people learned that radiation could also cause cancer, but it was first thought that this was due to prolonged ulceration of skin from repeated high level exposures. Because of this theory, the first radiation protection recommendations were aimed at avoiding gross tissue damage. This gave rise to the tolerance dose which was a form of threshold concept of radiation injury. In 1934, the Advisory Committee on X-Ray and Radium Protection proposed that a "safe level" of radiation was 0.1 r/day or 25 r/yr to the whole body (National Council on Radiation Protection and Measurements 1934).

During the 1930's, concern began to develop over the possible genetic effects of ionizing radiation based upon the classic studies of Muller (1940) using Drosophila. At that time, recommendations were also being formulated to control both external and internal exposures to radium. This led to the radium body burden standard of 0.1 μg recommended by the National Committee on Radiation Protection and Measurements in 1941. Between 1941 and 1946, the U. S. Atomic Energy Project began to develop large research programs to study the biological effects of radiation at the National Cancer Institute, the Universities of Chicago and Rochester and Oak Ridge; however, these were begun under tight war-time security. In 1949, the National Committee on Radiation Protection and Measurements lowered the recommended maximum permissible dose for external radiation to 0.3 r/week. This was based upon the growing awareness that even small doses of radiation could be harmful and that radiation exposures should be kept as low as possible. For genetic effects, the threshold concept began to be replaced by a linear, non-threshold risk concept in the late 1940s. These newer concepts of radiation health effects and protection philosophy were described by the National Committee on Radiation Protection and Measurements in 1954.

In 1956 and 1957, the basic permissible dose for radiation workers was lowered to 5 rem/yr and a general population exposure guideline was established at 0.5 rem/yr. This mainly resulted from studies of the genetic effects of radiation by the National Academy of Sciences, Committee on the Biological Effects of Atomic Radiation (National Academy of Sciences 1956). These whole-body radiation exposure guidelines still apply today and, surprisingly, they are not very different from those recommended more than 50 years ago, Table II-1. However, one important concept that did change with new knowledge that was developed during this period of time is the basis for setting occupational exposure standards. Having set aside the threshold dose concept and the possibility of a risk-free radiation exposure standard, new exposure guidelines were based upon the premise that radiation workers should not incur an added risk of dying greater than 1/10,000 per year. This is similar to risks in other comparable industries that are generally considered to be safe.

The description of the health effects of ionizing radiation that follows is intended to provide only a brief summary of information needed to understand the controversies that arise in evaluating radiation health risks discussed later in this report. More complete descriptions of radiation dosimetry and health effects can be found elsewhere (National Research Council 1980, 1972; United Nations Scientific Committee on the Effects of Atomic Radiation 1969, 1977; International Commission on Radiological Protection 1969). A brief glossary of technical terms used throughout this report is also provided at the end of the report.

Table II-1
Summary of Maximum Recommended External Whole-Body
Radiation Exposures in the United States

| Year | Recommended By | Occupational Guideline | Population Guideline |
|---|---|---|---|
| 1934 | NCRP[a] | 0.1 r/day[b]<br>25 r/yr | - |
| 1949 | NCRP | 0.3 r/week<br>15 r/yr | - |
| 1957 | NCRP | (Age-18) x 5 rem cumulative | 0.5 rem/yr |
| 1960 | Federal Government | 3 rem/13 weeks<br>(Age-18) x 5 rem cumulative | 0.5 rem/yr maximum<br>0.17 rem/yr average |

[a]National Council on Radiation Protection and Measurements.
[b]Exposure guidelines were originally stated in terms of roentgen measured in air.

Radiation Interactions in Tissues

Charged particles, uncharged particles and electromagnetic radiation interact with tissues in different ways (Upton 1982). As charged particles (electrons, positrons, protons, alpha and fission fragments) pass through tissue, they deposit energy through interactions of their electromagnetic fields with electrons in tissues (Figure II-1). Uncharged particles (neutrons) transfer most of their energy to tissues through collisions with nuclei of hydrogen atoms. After slowing down, the neutrons are absorbed mainly by nitrogen and hydrogen nuclei. Electromagnetic radiations (gamma and X-rays) transfer all or part of their energy to electrons through scattering and absorption. Most of these interactions occur with water molecules which make up about 75% of the total body mass, but radiation can also interact directly with atoms in structural molecules, proteins and DNA (the genetic material of cells) to produce ionizations and altered chemical bonds. Hydroxyl free radicals form when water is ionized and these may indirectly damage DNA and other structures including cell membranes. The relative importance of these direct and indirect interactions of radiation with tissues is not known.

On the cellular level, radiation damage may be fatal, it may be repaired without consequence or it may result in cells that are genetically altered but still viable. Cell deaths are not likely to be important unless massive tissue destruction occurs from very high radiation doses and critical organ functions are impeded. Most of the damage that occurs from low and intermediate levels of radiation is either removed by the body or repaired. This is demonstrated by the fact that cells continue to survive even in the presence of lifelong exposures to background and medical radiations. Radiation damage that alters DNA without killing the cells is very important. In somatic cells, this can lead to the development of fatal cancers and, in reproductive cells, it can lead to genetically transmitted defects in offspring.

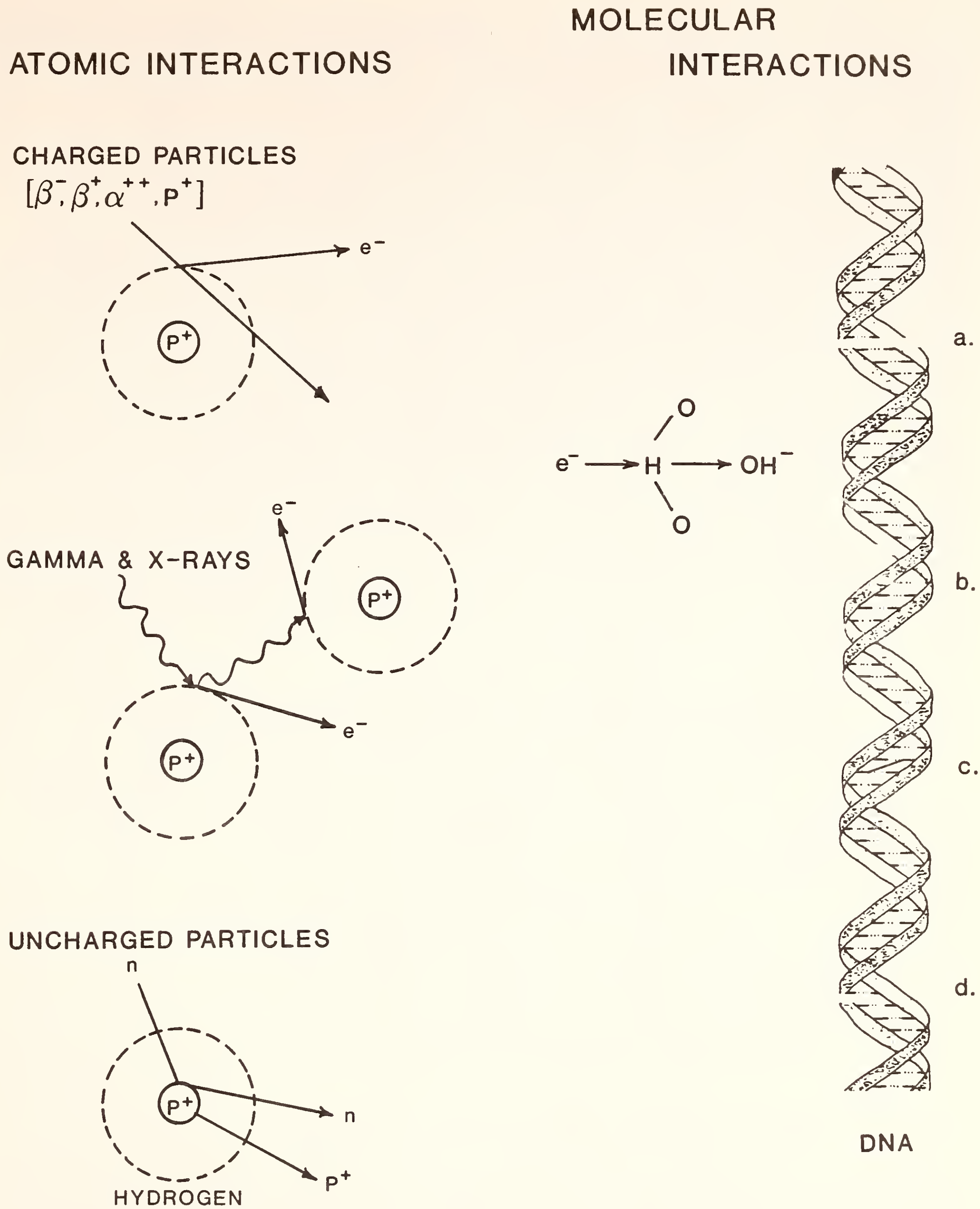


Figure II-1. Typical interactions of radiation with atoms and molecules of tissues. Charged particles, gamma, and X-rays interact with orbital electrons; neutrons lose energy through collisions with light nuclei until they are absorbed by hydrogen or nitrogen. Important molecular interactions include the formation of chemically reactive hydroxyl free radicals and alterations of DNA including (a) double strand breaks, (b) deletion of base pairs, (c) cross linking, and (d) single strand breaks (adapted from Upton 1982).

The rate of energy deposition along the track of an ionizing particle is called the linear energy transfer rate (LET). The LET varies for different types of radiation, for different energies, for different tissues and even along the length of an ionization track. A simple expression of the average LET is the total energy of the radiation divided by the average track length, keV/μm. X-rays, gamma and electrons produce low LET tracks; protons, neutrons, and alpha particles produce high LET tracks, Table II-2. For most biological effects, radiations that produce high LET tracks are more effective per unit dose than those with low LET tracks. The relative biological effectiveness (RBE) of different radiations varies from 1 to about 50 depending upon the type of effect being observed; however, RBE relationships are complicated by many dosimetric and biological factors. These observations led to the use a simplified system of average quality factors (QF) in radiation dosimetry in order to express doses in terms of their overall effectiveness for producing a biological effect (i.e. equivalent dose in rem is equal to dose in rad x QF). Quality factors for different types of radiation are also listed in Table II-2.

Alpha particles, protons and electrons incident upon the body from outside are mainly absorbed in skin and do not reach critical internal organs. Alpha particles and protons produce very high LET tracks and they are absorbed within short distances in tissues. Electrons are low LET radiations, but they do not penetrate far in tissue because they normally have energies well below 1 Mev. Neutrons, gamma and X-rays are important radiations from external sources because they can penetrate greater distances in tissue. Neutrons produce high LET ionization tracks, but they may not interact with atoms in tissues until they are deep inside the body. Gamma and X-rays penetrate tissues easily because they generally have low LET and sufficiently high energies.

Table II-2

Linear Energy Transfer (LET) of Radiation in Body Tissues and Quality Factors Assigned for the Purpose of Radiation Dose Calculations.[a]

| Type of Radiation | Energy MeV | Approx. LET keV/μm | Quality Factor | Average Range mm |
|---|---|---|---|---|
| X-ray or Gamma | 0.1 | 3 | 1 | 40 |
| | 1 | 0.3 | 1 | 100 |
| | 10 | 0.3 | 1 | 300 |
| Electrons or Positrons | 0.1 | 0.4 | 1 | 0.1 |
| | 1 | 0.2 | 1 | 4 |
| | 10 | 0.2 | 1 | 40 |
| Protons | 1 | 40 | 10 | 0.025 |
| | 10 | 5 | 10 | 1.2 |
| Neutrons | 1 | 50 | 10 | 50 |
| | 10 | 5 | 10 | 100 |
| Alpha Particles | 1 | 200 | 20 | 0.005 |
| | 10 | 100 | 20 | 0.1 |

[a]References Hine and Brownell 1956; Attix _et_ _al_. 1969; National Council on Radiation Protection and Measurements 1971.

Monitoring External and Internal Radiation Exposures

Exposures to people from external radiation sources are normally monitored using film badges, thermolumeniscent dosimeters and ionization chamber instruments. Dosimeters worn on clothing near the midline of the body are used to measure whole-body exposures; those worn on fingers or wrists measure partial body exposures to the extremities. Film badges and thermolumeniscent dosimeters record the integrated exposures over all of the time that they are worn. Ionization chamber instruments are most often used to measure instantaneous exposure rates or exposures over short intervals of time. Calibration of these dosimetry devices is accomplished by exposing them to standard radiation sources for fixed periods of time. Calibration curves are then constructed in order to interpret the readings of devices worn by individuals.

Personnel dosimeters and ionization chamber instruments measure radiation incident upon the body surface. Exposures to internal organs may be considerably less than those at the surface of the body due to absorption of radiation by the overlying tissues. This depends on the type and energy of the incident radiation. For example, Kerr (1979) estimated that for gamma and neutron radiations the doses to bone marrow (also midline organs) of Japanese atomic-bomb survivors were only about 50% and 25% of the doses at the surfaces of their bodies respectively. Laboratory studies by Ashton and Spires (1979) provide a method for estimating the ratios of tissue dose/air dose for different energy gamma radiations. The ratios range from 0.2 to nearly 1 for gamma energies between 0.05 and 2 Mev. Thus, significant corrections must be made when estimating tissue doses from the exposure rates measured in air.

Radiation doses to body organs from internal radioactivity can only be calculated from information on the amounts that were taken in by inhalation, ingestion or through wounds. This requires the use of mathematical models to calculate deposition, systemic absorption, organ uptake, retention and excretion of the radioactivity. Examples of these models are shown in Figure II-2. Complete descriptions of the models and of their applications are given in Publication 30 of the International Commission on Radiological Protection (1979).

For radioactivity inhaled in a soluble form, its absorption from the respiratory tract may be rapid and nearly complete. The absorbed radionuclides are translocated to other organs or excreted in urine and feces depending upon their chemical properties. For example, cesium and tritium distribute throughout the body; strontium and radium concentrate in bone; lanthanide and actinide elements distribute mainly between bone and liver; and iodine is taken up by the thyroid. For radioactivity inhaled in relatively insoluble particles, retention of the particles in lung and pulmonary lymph nodes persists for hundreds of days. Clearance of the deposited particles to the gastrointestinal tract and absorption of solubilized radioactivity into the systemic circulation may be very slow causing the lung and lymph nodes to receive the largest radiation doses.

For ingested radioactivity, absorption into the systemic circulation and uptake by different organs depends mainly on the chemical form of the material as described above. Unabsorbed radioactivity passes directly through the gastrointestinal tract and the highest radiation doses are most often delivered to the lower large intestine. Radioactivity entering the body through wounds may be retained at the wound sites, translocated to regional lymph nodes or be absorbed into the systemic circulation. Again, the clearance of this material depends on its chemical form with the more soluble forms being absorbed more quickly than insoluble forms.

Estimations of organ doses to accidently exposed individuals from internal radioactivity are markedly improved when bioassay measurements are available. The retained body burdens may be directly measured by external counting or estimated from the amounts of radioactivity appearing in excreta. For long-lived radionuclides that are retained in the body for extended periods of time, bioassay measurements can be used to estimate the initial exposure levels even after many years. Autopsy tissue samples can also be analyzed for this purpose.

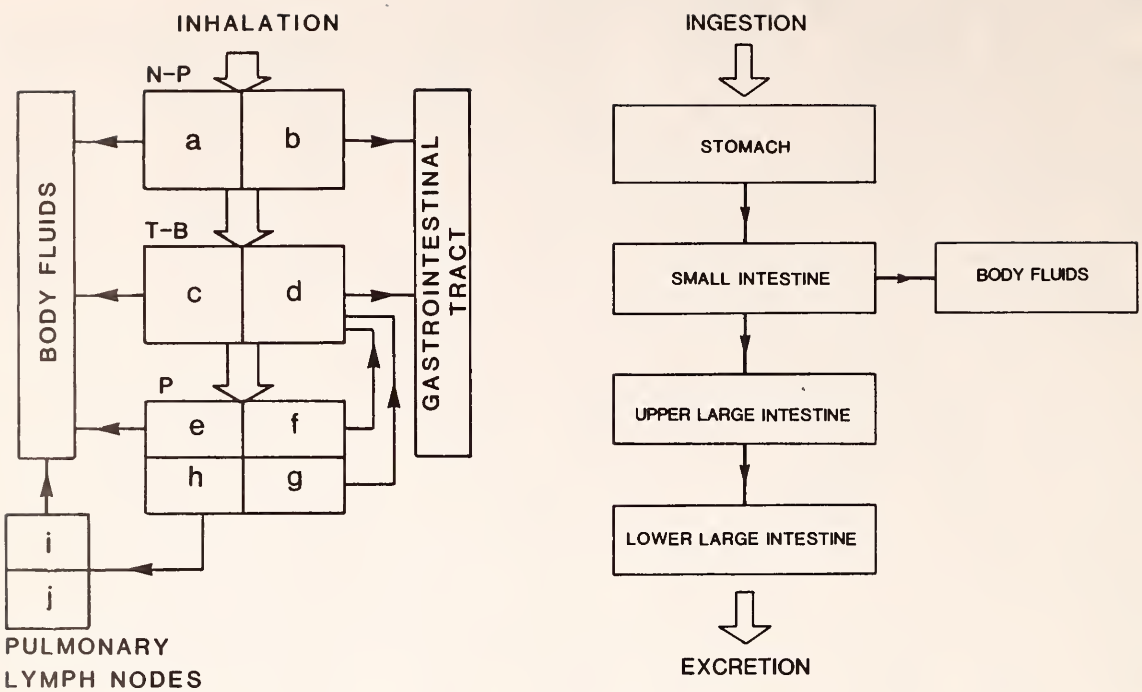


Figure II-2. Illustration of models used to calculate radiation doses to tissues from inhaled or ingested radioactivity. Inhaled material deposits in the nasopharyngeal (N-P), tracheobronchial (T-B), and pulmonary (P) regions of the respiratory tract. Particles are cleared to the pulmonary lymph nodes and gastrointestinal tract; soluble material may be absorbed into the systemic circulation. Ingested material may be absorbed into body fluids, mainly from the small intestine, or be excreted in feces (International Commission on Radiological Protection 1979).

It is important to emphasize that there are significant differences between measured external radiation levels and doses to internal organs. Partial body exposures to extremities and single organ doses from internal radioactivity also have important distinctions from whole-body exposures when evaluating health risks. Ultimately, it is necessary to know the doses to the specific organs that are likely to be affected in order to estimate the risk of developing a disease or to estimate the probability that radiation was the primary cause of an observed disease.

Acute Radiation Injuries

Acute radiation injuries generally refer to noncancer effects that result from high radiation doses delivered over short periods of time. These effects are most frequently seen within days or weeks of a high level external radiation exposure and include widespread destruction of blood forming cells in bone marrow, of cells lining the gastrointestinal tract and of cells comprising the lung, liver, thyroid or skin. The exposures causing these injuries are easy to identify because they only occur in severe accident situations and there is little doubt in associating these injuries with the accidents because they occur close in time.

In other accident situations, large amounts of radioactivity may be taken internally leading to irradiation of body organs over longer periods of time. This may cause loss of organ function and even death several years after the initial exposure. These types of accident situations are unusual and few have occurred outside of specialized work environments. Accidents that may occur

in the general environment and lead to high internal depositions of radioactivity are also likely to have significant external radiation exposures. One example of this kind of exposure occurred with Marshall Island residents and Japanese fishermen who were exposed to high levels of nuclear weapons fallout and ingested radioiodine. They later developed hypothyroid conditions, thyroid nodules and thyroid cancers. This is discussed in Section V of this report. However, this type of exposure may not be a major problem in future accidents because of the increased awareness of risks from ingested and inhaled radioactivity and the need to evacuate areas contaminated with radioactivity or to otherwise avoid such exposures.

The types of health effects that may be observed soon after whole-body radiation exposures are listed in Table II-3. Approximate doses at which 50% of the irradiated people would be expected to show these effects are also listed (Lushbaugh 1981, U. S. Nuclear Regulatory Commission 1975). Doses at which 10% incidence would be expected are approximately one-fourth of those listed. Protraction of the radiation exposure increases the dose required for each level of effect. For example, one mathematical model for predicting mortality estimates the 50% lethal dose in rad by using the expression;

$$LD_{50} = 345\ t^{\ 0.26}$$

where t is the time in weeks over which the radiation is delivered and 345 rad is the 50% lethal dose for low LET radiation delivered in less than one week. The equivalent 10% and 90% lethal dose values are 118 rad and 585 rad, respectively (Lushbaugh 1981).

Table II-3

Acute and Delayed Noncancer Effects of Low LET Radiation and Approximate Single Doses for 50% Incidence in People (Lushbaugh 1981, U. S. Nuclear Regulatory Commission 1975).

| Irradiation | Health Effect | Rad Dose for 50% Incidence |
|---|---|---|
| Whole Body (External) | Anorexia | 150 |
| | Nausea | 210 |
| | Fatique | 220 |
| | Vomiting | 280 |
| | Epilation | 300 |
| | Diarrhea | 350 |
| | Hemorrhage | 400 |
| | Mortality | 345 |
| Thorax (External) | Pneumonitis | 1050 |
| | Mortality | 1700[a] |
| Lung (Internal) | Mortality | > 10,000[a] |
| Abdomen (External) | Mortality | > 1500 |
| Gastrointestinal Tract (Internal) | Mortality | > 3000[a] |
| Reproductive Organs (External) | Sterility Males (temporary) | 80 |
| | Females (permanent) | 200 |

[a]Projected from studies in laboratory animals.

Supportive medical treatment decreases early mortality for a given level of radiation exposure (U. S. Nuclear Regulatory Commission 1975). Studies of leukemia patients who received whole-body irradiation as a treatment for their disease showed that people could survive about 3 times more dose if they had supportive medical care. This included measures to prevent infections (i.e. isolation and large doses of antibiotics) and transfusions of whole blood or platelets.

Acute effects of partial-body external irradiation or of internal radionuclides are also listed in Table II-3. Much larger radiation doses are required to produce mortality when only one or a few organs are irradiated as compared to when the whole-body is irradiated. Protraction of the irradiation by dose fractionation or as occurs naturally with internal radioactivity generally increases the $LD_{50}$ doses by several times. Models for predicting these and other effects have been mainly developed from studies in laboratory animals and the cited references should be consulted for further details. The summary given in Table II-3 is intended to provide approximate dose ranges at which health effects are likely to occur because they are sometimes discussed in litigations to imply what levels of radiation exposures may have occurred to people under circumstances where no actual dose measurements were available. They are much higher than dose ranges that are normally considered as low level exposures for which cancer induction later in life becomes the primary concern.

Cancer Risks from Radiation

Although cancer risks from high level radiation exposures had been known for many years, the possibility that low level exposures (less than about 100 rad) could cause cancer was not considered seriously until increased levels of leukemia were first detected in American radiologists and in Japanese atomic bomb survivors (Lewis 1957, 1963). Since these reports, many types of cancers have been shown to be caused by radiation at exposure levels between 100 and 200 rad. In fact, the National Research Council Committees on the Biological Effects of Ionizing Radiations (1972, 1980) have estimated that natural background radiation may cause 1 to 2% of all cancers that occur in people.

Evidence that radiation causes many different types of cancer is derived from four major sources; (1) people who were exposed to direct radiation from atomic weapons detonations or to radioactive fallout, (2) medical patients treated with radiation in therapy, (3) workers in industries that use radiation or radioactive substances, and (4) laboratory studies using animals. A summary of irradiated human populations that experienced excess incidences of different types of cancers is shown in Table II-4. Epidemiologic studies of these populations have been used to derive mathematical relationships between radiation doses to the effected organs and added cancer risk. Adequate quantitative relationships are available for leukemia, and cancers of the thyroid, breast and lung. These include information on risk as a function of dose, age at exposure, age at diagnosis, and sex. Dose-effect relationships for other cancers shown in Table II-4 are less certain, mainly because of their low sensitivities to induction by radiation.

Most of the cancer dose-effect relationships were derived from studies of the Japanese atomic bomb survivors and patients with ankylosing spondylitis treated with X-rays. Their exposures mainly involved external low LET radiations as did exposures to medical patients treated for tinea capitis, enlarged thymus and mastitis, women who were repeatedly fluoroscoped and the radiologists. Few epidemiologic studies are available on populations with internally deposited radionuclides. They include Marshall Island residents who ingested beta-emitting radioactive iodine, medical patients who were injected with thorotrast, dial painters who ingested radium, and uranium miners who inhaled radon and its radioactive daughter products.

Because few studies are available on people exposed to internally deposited radionuclides, most of our information to project these cancer risks is derived from studies in laboratory animals. Although there is reluctance on the part of many health specialists to use information

Table II-4

Summary of Epidemiologic Studies of Human Populations that Provided Quantitative Relationships (indicated by Q) or Simple Associations (indicated by A) Between Radiation and Increased Cancer Risk (adapted from Upton 1982)

| | NUCLEAR WEAPONS | | MEDICAL PATIENTS | | | | | | | | | OCCUPATIONAL EXPOSURES | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Type of Cancer | Japanese Atomic Bomb Survivors | Marshall Island Residents | Ankylosing Spondylitis (X-Ray) | Ankylosing Spondylitis (Radium) | Thorotrast | Tinea Capitis | Infants with Thymus Irradiation | Head and Neck X-Ray Therapy | Radioiodine Therapy | Chest Fluoroscopy | Mastitis Patients (X-Ray) | Radiologists | Radium-Dial Painters | Uranium Miners | Nuclear Workers |
| Leukemia | Q | | Q | A | Q | A | A | | | | | A | A | | |
| Thyroid | Q | Q | | | | Q | Q | Q | A | | | | | | |
| Breast | Q | | | | | | | | | Q | Q | | | | |
| Lung | Q | | Q | | | | | | | | | | | Q | |
| Stomach | Q | | Q | | | | | | | | | | | | |
| Intestine | Q | | Q | | | | | | | | | | A | | |
| Esophagus | Q | | A | | | | | | | | | | | | |
| Pancreas | Q | | Q | | | | | | | | | | | | |
| Urinary T. | Q | | A | | | | | | | | | | | | |
| Liver | Q | | | | Q | | | | | | | | | | |
| Lymphoma | Q | | Q | | | | | | | | | A | | | |
| Bone | | | A | Q | | | | | | | | | Q | | |

obtained from studies in laboratory animals to derive quantitative risk relationships for people, animal studies have provided reliable information on the relative hazards of different types of radiation that can be used to extend the available epidemiologic information to evaluations of other human exposure situations. A summary of radiation induced cancers in laboratory animals is given in Table II-5.

## Models of Radiation Cancer Risk

Most people receive only small exposures to ionizing radiation during their lifetimes. Natural background accounts for 5 to 10 rem of exposure to the whole-body which is distributed uniformly throughout life. Exposures to medical diagnostic radiation add another 5 to 10 rem for an average individual, but more of this is mainly received late in life as normal health problems increase. Workers in radiation related occupations are permitted receive up to 250 rem of whole-body exposure; however in practice, few workers receive more than 50 rem. Thus, the range of dose for which cancer risk information is most needed is 10 to 100 rem.

Cancer risks for doses of radiation between 10 and 100 rem are difficult to estimate because of statistical uncertainty. For example, the average cancer risk factor for whole-body radiation appears to be about 20 excess cancers per year per million person rem. If 20,000 people each received 10 rem of whole-body radiation in mid-life, then 80 to 140 excess cancers would be

Table II-5

Summary of Studies in Laboratory Animals that Provide Quantitative Relationships (Indicated by Q) or Simple Associations (Indicated by A) Between Cancer Risks and Different Types of Radiation Exposures

| | Dogs | | | Rats | | | Mice | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Type of Cancer | Gamma and X-Ray | Alpha | Beta | Gamma and X-Ray | Alpha | Beta | Gamma and X-Ray | Alpha | Beta | Neutrons |
| Leukemia | Q | A | Q | A | | | Q | | Q | Q |
| Thyroid | Q | | | Q | | Q | Q | | Q | |
| Breast | | | | Q | | | A | | | |
| Lung | A | Q | Q | A | Q | Q | A | Q | Q | Q |
| Stomach | | | | Q | | | Q | | | Q |
| Intestine | | | | | | | Q | | | Q |
| Esophagus | | | | A | | | Q | | | |
| Pancreas | | | | | | | A | | | |
| Urinary T. | | | | Q | | | Q | | | Q |
| Liver | | Q | Q | A | | Q | A | | | |
| Lymphoma | | | | | | | Q | | | Q |
| Bone | | Q | Q | Q | Q | Q | Q | Q | Q | |

predicted. This is in addition to the 4000 (± 65 SD) spontaneously occurring cancers. To demonstrate the radiation effect would require an epidemiologic study covering about 35 yr of observations, and then, the number of radiation induced cancers would just barely be statistically significant. Only the Japanese atomic bomb survivor population has a sufficient number of people (approximately 120,000) with adequate followup time to estimate cancer risk in the low dose range. However, studies of this population are complicated by other factors such as the possible influence of traumatic injuries, uncertain dosimetry and the lack of a good control population. Other smaller irradiated populations have been studied to provide scientific collaboration of the results obtained from the Japanese studies and to include other forms of radiation exposures. Because these populations have fewer people or insufficient followup times, only the results from radiation exposures greater than 100 rem have generally been useful. To use these results in predicting cancer risks for exposures between 10 and 100 rem requires the use of mathematical models for extrapolation to the lower dose ranges. Herein, lies much of the current radiation cancer risk controversy.

Two model forms have been used to express radiation induced cancer risk; the absolute risk model and the relative risk model. The absolute risk model usually assumes that the increased cancer risk for a given exposure level (excess cases per year) begins after a latent period and continues at a constant or variable level for the expression time. Afterwards, the added risk may decline or disappear. The relative risk model assumes that after the latent period, excess cancer risk is a multiple of the spontaneous cancer rate over the expression time. These models are arithmetically consistent with each other when applied to a single set of data over the same period of observation. Both must account for the same number of excess cancers over the study period and both will predict the same excess risk for another population that would be irradiated

in a similar manner and studied for the same time period. However, the two model predictions may differ markedly beyond the period of time covered by their epidemiologic data base and it has not been determined which, if either, model is more appropriate. Because most cancer risks increase markedly in old age, the relative risk model often predicts 3 to 4 times more cancers than the absolute risk model when lifetime projections are made (National Research Council 1980). This problem is also significant in projecting risks for *in utero* irradiation which may be higher than risks from exposures of adults. In this case, it is not known how long the higher risks of *in utero* radiation may continue during a person's lifetime.

Mathematical differences between the predictions of the absolute and relative risk models disappear when the appropriate cancer latent periods, expression times and age sensitivity relationships become known. For leukemia and bone cancers the latent period lasts for 2 to 5 yr and the expression time lasts for about 30 yr after irradiation. Less is known about other cancer types which may have latent periods of 20 yr or more and expression times well beyond 30 yr.

One additional important difference between the relative and absolute risk models is in their predicted patterns of excess cancer risk. The relative risk model predicts that more radiation induced cancers will occur in older people and in people with the highest risks aside from those caused by the irradiation. The latter high risk category includes people with more than average genetic susceptability to cancer, smokers and those who are exposed to other carcinogenetic agents. The absolute risk model suggests a uniform pattern of excess cancer risk in an irradiated population regardless of other risk modifying factors. These important differences between the relative and absolute risk models can and should be investigated with further laboratory and epidemiologic studies.

Coupled with the use of an absolute or relative radiation cancer risk model is a mathematical dose-effect relationship. This relates the excess risk of developing a cancer to the amount of dose received. Several examples are shown in Figure II-3. The most common mathematical forms that have been used are;

1. Linear Risk = $\alpha_0 + \alpha_1 D$
2. Quadratic Risk = $\alpha_0 + \alpha_2 D^2$
3. Linear-Quadratic Risk = $\alpha_0 + \alpha_1 D + \alpha_2 D^2$

where $\alpha_0$ is the spontaneous incidence, $D$ is the dose in rem or rad and $\alpha_1$ and $\alpha_2$ are fitted dose coefficients obtained from analyses of epidemiologic or laboratory studies. The coefficients $\alpha_1$ and $\alpha_2$ can be expressed in terms of absolute risk (cancers per unit population per unit dose or dose squared) or relative risk (fractional increase in cancer risk per unit dose or dose squared). Within the dose range of any set of experimental observations, there is little or no difference between the numbers of excess cancers represented by each mathematical expression. The different forms are sufficiently adjustable in the fitting process and the data are relatively scattered so that it is impossible in most cases to select the best mathematical form.

However, important differences occur in the model predictions of cancer risks outside of the dose range represented by the original data. This is especially important in the low dose region. Here, the linear function predicts the largest risk and the quadratic function predicts the lowest risk. The linear function is used most frequently because it is not likely to underestimate cancer risks at low doses. It also seems to be most appropriate for high LET radiations for which more data are available in the low dose region. The linear-quadratic function is gaining in acceptance because it is the most flexible for fitting dose-effect information over all dose ranges and the fitting process automatically adjusts for the relative importance of the linear and quadratic components of the dose-effect information. For mixtures of low and high LET radiations, the linear-quadratic and linear functions may be combined in several ways to project the increased cancer risk. For example, the function;

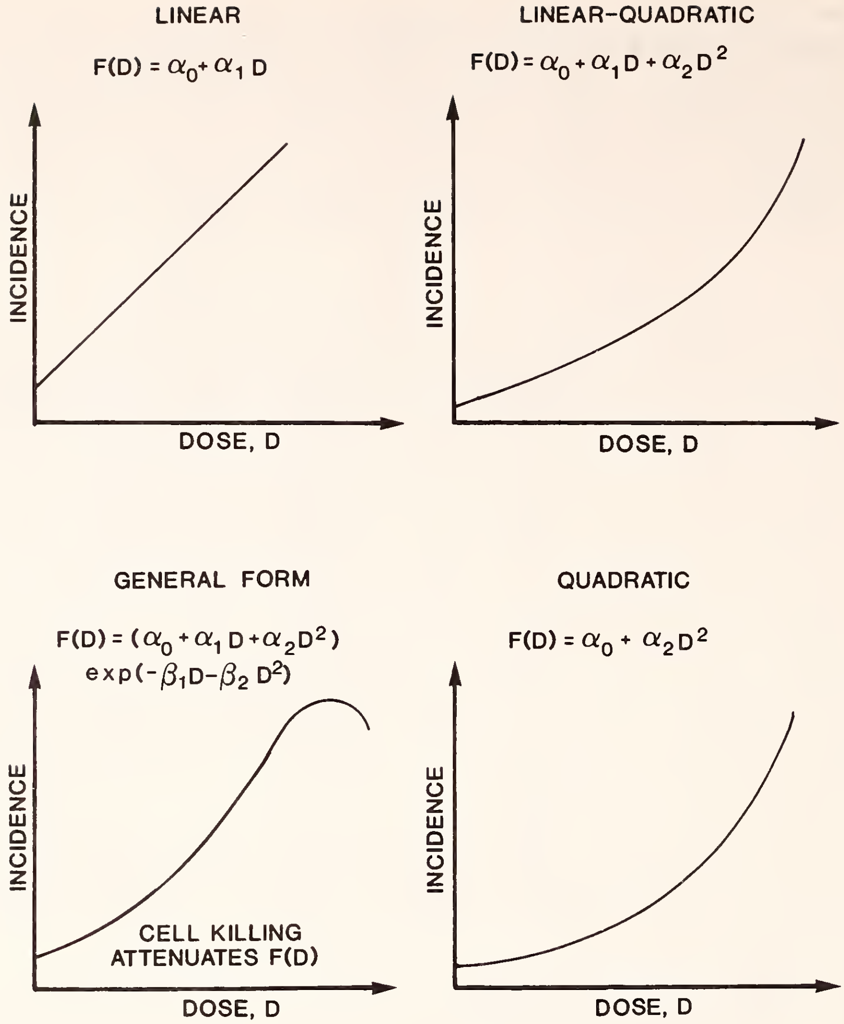


Figure II-3. Mathematical relationships used to analyze radiation dose-effect information and predict risks for populations exposed to all levels of radiation dose. Coefficients of dose terms, α and β, are determined for each cancer by fitting the function to epidemiologic or laboratory toxicology data (adapted from National Research Council 1980).

$$\text{Risk} = \alpha_0 + \alpha_1 D_\gamma + \alpha_2 D_\gamma^2 + \beta_1 D_n$$

could be used for a mixture of gamma dose, $D_\gamma$, and neutron dose, $D_n$, where the coefficients, $\alpha_1$, $\alpha_2$ and $\beta_1$, are obtained by fitting the dose-effect information. Unfortunately, as the dosimetry of the exposure becomes more complex and the number of fitted coefficients increases, uncertainty in each mathematical parameter may grow until it is no longer possible to make clear choices as to the most appropriate function to use.

In the high dose region of radiation dose-effect studies (i.e. at acute whole body doses greater than 300 rem or single organ doses greater than 3000 rem), the number of cancers produced per unit dose may actually decrease with increasing dose (National Research Council 1980, Cuddihy 1982). This is due to life span shortening from diseases other than cancer, to cell killing and

to the continued accumulation of dose beyond the points at which cancers have been initiated in individuals. As a result, using cancer risk information developed from high dose studies can lead to underestimating radiation cancer risks for people who receive low radiation exposures. Mathematical functions have been incorporated into dose-effect relationships to correct for this difficulty, but they require knowledge of additional parameters. For example, the linear, linear-quadratic and quadratic functions have been multiplied by negative exponential factors such as;

$$e^{-TD} \quad \text{or} \quad e^{-T_1D-T_2D^2}$$

where T, $T_1$ and $T_2$ are fitted constants. However, adding these corrections increases the uncertainty in risk projections below the dose range of the original data. From a risk assessment point of view, the need to use high dose correction factors for specific sets of data indicates that the data are not well suited to estimating cancer risks in populations that receive low radiation doses.

As described in the National Academy of Sciences BEIR Committee Report (1980), the overall process of estimating cancer risk due to a radiation exposure is complicated. To some extent, this results from their inability to identify the most appropriate risk model (absolute or relative risk model) and dose-effect relationship (linear, linear-quadratic or quadratic form) for use in predicting different types of cancer. The complication also results from their determination to provide different risk function coefficients for each sex and for each of five age groups even when there was an insufficient data base. As a result of these complications, more than six ways of calculating radiation cancer risk from a single exposure are provided in the BEIR report. Excluding the use of the quadratic dose-effect relationship, most of the cancer risk projections for a single type of exposure are within a factor of 10, but using all mathematical models the largest risk projection can be 50 times higher than the smallest projection. This is a substantial degree of uncertainty, too large for many risk assessment purposes.

To illustrate how radiation cancer risks may be estimated, one set of risk factors using the absolute model derived from the BEIR report is given in Table II-6. The excess annual lung cancer risk for a male exposed to 100 rad at age 35 is calculated as;

$$(5.1 \times 10^{-6}/\text{yr} \cdot \text{rad}) \times 100 \text{ rad} = 5.1 \times 10^{-4}/\text{yr}$$

This risk would be expected to begin about 11 yr after exposure and continue for 20 yr. Thus, the total added risk is $1.02 \times 10^{-2}$. This is illustrated in Figure II-4. The risk of an average U. S. male developing lung cancer between 45 and 65 yr of age is $2.7 \times 10^{-2}$ (U. S. Department of Health and Human Services 1982). Therefore, 100 rad to lung tissue would increase the risk of developing lung cancer by the factor;

$$\frac{1.02 \times 10^{-2} + 2.7 \times 10^{-2}}{2.7 \times 10^{-2}} = 1.38$$

Risk calculated for the same exposure by the relative risk model is also illustrated in Figure II-4 and there is no discrepancy in the total estimated risks up to the end of the assumed expression period. A discrepancy between model calculations arises if the man were to live to age 75 and the radiation lung cancer risk continued throughout his entire lifetime. Then his risk of developing lung cancer by the absolute risk model calculation is;

$$(5.1 \times 10^{-4}/\text{yr}) \times 30 \text{ yr} = 1.5 \times 10^{-2}$$

Table II-6

Estimated Annual Excess Cancer Incidence per Million People Per Rad of Exposure to Ionizing Radiation (National Research Council 1980).[a]

| | | Age at Exposure | | | | |
|---|---|---|---|---|---|---|
| Site | Sex | 0-9 | 10-19 | 20-34 | 35-49 | 50+ |
| Lung | M-F | - | 0.54 | 2.45 | 5.10 | 6.79 |
| Breast | F | - | 7.3 | 6.6 | 6.6 | 6.6 |
| Thyroid | M | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 |
| | F | 5.8 | 5.8 | 5.8 | 5.8 | 5.8 |
| Leukemia | M | 3.9 | 1.81 | 2.54 | 1.88 | 4.22 |
| | F | 2.5 | 1.17 | 1.63 | 1.21 | 2.70 |
| Stomach | M-F | 0.4 | 0.4 | 0.77 | 1.27 | 3.35 |
| Intestine | M-F | 0.26 | 0.26 | 0.52 | 0.84 | 2.23 |
| Pancreas | M-F | 0.24 | 0.24 | 0.45 | 0.75 | 1.97 |
| Urinary | M-F | 0.04 | 0.23 | 0.50 | 0.92 | 1.62 |
| Liver | M-F | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| Esophagus | M-F | 0.07 | 0.07 | 0.13 | 0.21 | 0.56 |
| Lymphoma | M-F | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 |
| Bone | M | 0.09 | 0.04 | 0.06 | 0.04 | 0.09 |
| | F | 0.05 | 0.03 | 0.04 | 0.03 | 0.06 |

[a]Risk factors apply to the expression time 11-30 yr after exposure for all cancers except leukemia and bone cancer. The expression time for leukemia and bone cancer is 2-27 yr after exposure.

Using the relative risk model calculation, the man's added risk of developing lung cancer is;

$$(1.38 - 1)\ 6.6 \times 10^{-2} = 2.5 \times 10^{-2}$$

where $6.6 \times 10^{-2}$ is the risk of a U. S. male developing lung cancer between the ages of 45 and 75 yr (U. S. Department of Health and Human Services 1982).

Attributable Risk Calculations

Throughout the following discussion it is important to keep in mind that risk factors derived for radiation induced cancer are based upon statistical studies of large populations. The studies involved few types of radiation exposures and they contain very limited information on the influence of age at exposure, age at diagnosis of cancer, dose protraction, risk at low doses and other risk modifying factors. Undoubtedly, they can be applied in evaluating cancer risks in similar populations that are exposed to radiation in similar ways, but a more extended use of this data is often required. The first uses of radiation cancer risk information were in evaluating risks to workers in nuclear industries and to members of the public who might be exposed to radiation in the environment or even in medical applications. For example, using risk factors reported by the BEIR Committee it is possible to estimate that if workers in nuclear industries received the maximum allowed exposure of 5 rem/yr between 20 and 65 yr of age, their risk of developing a cancer would increase by 5 to 50%. In terms of absolute risk of death from cancer, maximum industrial exposures could represent an increased lifetime risk of $85 \times 10^{-4}$ to $850 \times 10^{-4}$. Because the average exposure of workers in nuclear industries is only about 0.1 rem/yr (U. S. Nuclear Regulatory Commission 1977), their average risk of dying of a cancer caused by their occupation is $1.7 \times 10^{-4}$ to $17 \times 10^{-4}$.

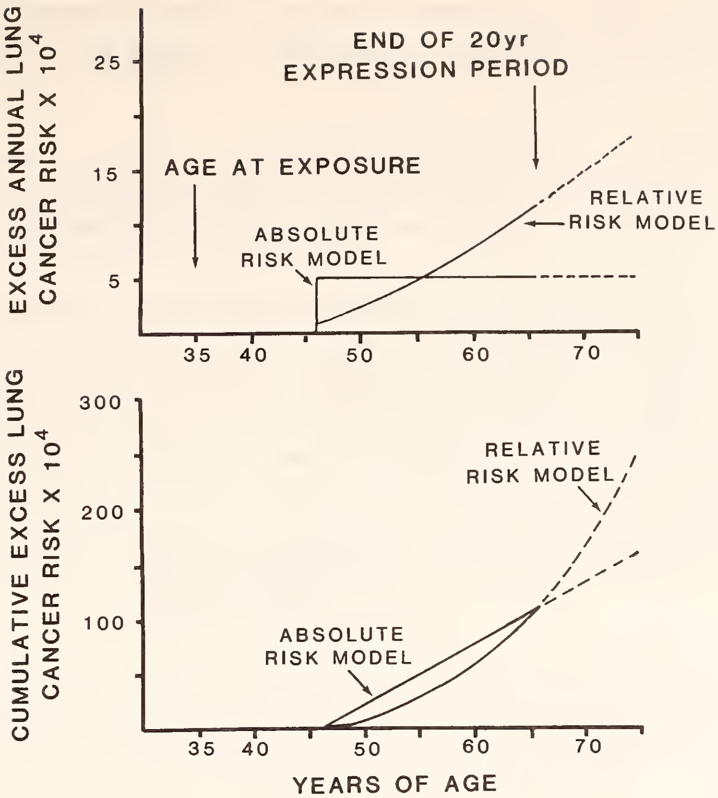


Figure II-4. Sample calculation of lung cancer risk projected for a typical U.S. white male who is exposed to 100 rad at 35 years of age. Cancer risk is projected for a lifespan of 75 years using both absolute and relative cancer risk models. A latent period of 11 years is assumed.

In calculating cancer risk for a large population of workers theoretically exposed to 250 rem, the risk factors are being applied within the appropriate dose range. Studies of the Japanese atomic bomb survivors showed excess cancers above about 50 rad of external radiation. In calculating cancer risk for workers exposed to 0.1 rem/yr, less than a total of 5 rem over their lifetimes, we are clearly below the dose range in which excess cancers have been detected in previous exposed populations. Although the uncertainties of this low dose extrapolation are unknown, this use of the risk factor information provides an important perspective on risk to radiation workers.

Another use of risk factors for radiation induced cancers was proposed by the U. S. Congress (Orphan Drug Act 1983). Congress requested the Secretary of Health and Human Services to publish tables of information to estimate the likelihood that cancers developed by people were caused by a previous radiation exposure. The original concern focused on thyroid cancers developed by people exposed to radioiodine in nuclear weapons fallout, but the mandate of Congress extends beyond this to other radiation induced cancers. Similar calculations have been used in radiation injury litigations where it is necessary to present testimony on whether a cancer developed by an individual was, more likely than not, caused by a previous exposure to radiation. These types of applications are now commonly referred to as relative attributable risk calculations.

The likelihood that a cancer was caused by radiation has been estimated by using either the absolute or relative risk model calculations. Using the absolute model, the fractional causation or assigned share attributable to the radiation exposure is expressed as;

$$\text{Fractional Causation} = \frac{\begin{matrix}\text{Excess Cancers per} \\ \text{Unit Population per} \\ \text{Unit Dose}\end{matrix} \times \text{Dose}}{\begin{matrix}\text{Expected Cancers} \\ \text{per Unit Population}\end{matrix} + \begin{matrix}\text{Excess Cancers per} \\ \text{Unit Population per} \\ \text{Unit Dose}\end{matrix} \times \text{Dose}}$$

The expected cancer risk should include all lifestyle factors that contribute to the development of cancer in an individual, although many such factors are appropriately accounted for in the epidemiological data bases. Special consideration should be given to hereditary factors, exposures to medical radiation and other carcinogenic agents, age, location of residence, smoking and dietary factors. Using the relative cancer risk model, fractional causation is expressed as;

$$\text{Fractional Causation} = \frac{\begin{matrix}\text{Fractional Increase} \\ \text{in Risk per Unit Dose}\end{matrix} \times \text{Dose}}{1 + \begin{matrix}\text{Fractional Increase} \\ \text{in Risk per Unit Dose}\end{matrix} \times \text{Dose}}$$

This model assumes that radiation simply multiplies an individual's risk of developing a cancer due to all other causes. When fractional causation from radiation exceeds 0.5, using either model calculation, it may be argued that the cancer was, more likely than not, caused by the radiation exposure.

The radiation cancer risk tables recently provided to Congress by the Secretary of Health and Human Services recommends use of the relative (multiplicative) risk model calculation in evaluating all situations except for lung cancer developed by smokers (National Institutes of Health 1985). The absolute risk model calculation is difficult to use for this purpose because its use requires specific lifestyle information for an exposed individual which does not lend itself to presentation in simple tables. The relative risk model has never been demonstrated to apply to radiation risk calculations regardless of an individual's exposure to other carcinogenic agents. It is also unclear as to how cancer risks from multiple agents might be incorporated into the fractional causation relationship. Even if the assumptions of the relative risk model can be demonstrated, people who have lifestyle factors that increase their spontaneous risk of developing cancer are contributing to increasing the probability that an induced cancer will actually occur. Consequently, employers might well avoid placing smokers, women and individuals over 40 years of age in jobs that involve exposures to radiation. Such a policy would have a major impact on employment practices with little or no scientific justification. It might also constitute a new way of establishing de facto occupational radiation exposure controls, because employers could avoid litigations over radiation induced cancers by not allowing exposures to more dose than could be conceived as of doubling the spontaneous risk of developing the most radiation sensitive types of cancer. Unfortunately, the basic uncertainty in estimating radiation cancer risk is considerable, as discussed above and the whole process of calculating cancer risk attributable to radiation is probably too imprecise to be used in resolving most litigations.

## Genetic Effects of Ionizing Radiation

Genetic damage refers to alterations in the genes and chromosomes of sperm and ova that lead to embryonic deaths or inherited disorders in progeny. A gene is made up of many nucleotides in a specific sequence and thousands of genes are organized in an equally specific sequence to form a chromosome. These determine characteristics of people and changes in gene structures result in

genetic or inherited disorders. Radiation may produce a wide range of genetic effects - from small and unnoticed changes in individual genes to complete chromosome breaks that have serious consequences if they are not repaired. Genetic damage from ionizing radiation probably occurs by similar mechanisms that cause somatic injuries leading to the development of cancers.

Concern over genetic effects of ionizing raidation has mainly focused on exposures to the total population rather than on exposures to radiation workers. In 1958, the International Commission on Radiological Protection recommended that the genetically significant dose to individuals from sources other than natural background and medical radiation should not exceed 5 rem. This pertains to radiation received before 30 yr of age and represents a dose about equal to that from natural background and other sources. On an annual basis the recommended limit for the general population is 170 mrem/yr. This is consistent with the population radiation exposure guideline derived from somatic risk considerations by taking 10% of the occupational limit of 5 rem/yr as a maximum, and one-third of this for the average exposure to individuals.

The incidence of radiation induced genetic effects appears to increase with increasing dose similar to cancer induction. The BEIR Committee suggests that data or radiation induced genetic effects are frequently represented best by the linear-quadratic dose-effect ralationship

$$\text{Incidence of Genetic Effects} = \alpha_0 + \alpha_1 D + \alpha_2 D^2$$

where $\alpha_0$ is the normal incidence of a genetic defect and $\alpha_1$, and $\alpha_2$ are coefficients of the dose terms obtained by fitting the mathematical function to measurements of genetic effects in radiation exposed populations. However, for assessing human genetic risk from low doses and dose rates of ionizing radiation, a linear extrapolation from studies using laboratory mice is used. This is because genetic effects of radiation have never been quantitated in human populations.

The most easily recognized of all genetic disorders in people result from single dominant gene mutations. These disorders are observed in the first generation and include malformations of digits and limbs, and diseases such as certain types of muscular distrophy, anemia and retinoblastoma. There are about 1500 dominant gene inheritable disorders (McKusick 1978) which affect about 1% of all people born. Recessive gene mutations are more difficult to detect unless they are linked to the X chromosome. Sex-linked recessive gene mutations are almost exclusively expressed in males and they occur in the first generation, like dominant gene mutations, because males have only one X chromosome. There are about 200 sex-linked inherited disorders (McKusick 1978) among which are the well-known examples, hemophilia and color blindness. Other recessive gene mutations are difficult to detect since the abnormalities may not occur for many generations because both members of a pair of homologous chromosomes must have the mutation in order to produce the trait. However, this rarely occurs and the mutation is likely to be removed from the population before it is observed. Recent information suggests that recessive mutations may not be completely recessive; a few percent are likely to affect the overall fitness of a population even in the heterozygous state (Crow 1982). If true, this may be the largest impact of recessive mutations on a population because its expression in the homozygous state is so rare.

A third type of gene mutation may cause disorders of complex etiology, manifested in constitutional and degenerative diseases, genital malformations and other anomalies expressed later in life. The expression of these disorders may be caused by the cumulative effect of many different genes and environmental factors or they may be single gene traits with incomplete penetrance. It has been estimated that 9% of all people born are affected by these irregularly inherited genetic disorders. The fourth type of genetic disorder results from chromosome breaks. These may cause gross disruptions of gene components so that infertility or embryonic deaths

occur. Even though this is the most severe type of genetic injury, it goes unnoticed in most cases and has little impact on population health and well-being. When the damage is less severe and the individual survives, physical abnormalities and mental retardation may result.

Ionizing radiation may cause some or all of these genetic disorders. Genetic risk factors for radiation estimated by the BEIR Committee from studies in laboratory animals are shown in Table II-7. As a rough estimate, between 50 and 200 rem of genetically significant dose per individual is thought to be required to double the spontaneous mutation rate and the level of mutant genes in a population. Of the potential genetic disorders, dominant and X chromosome-linked gene mutations are considered most serious and the only inherited disorders that may be caused by radiation and that are likely to be detected. Recessive and irregularly inherited genetic disorders may increase to new equilibrium levels in a population, but they are difficult to detect and their relationship to previous radiation exposures will be difficult to demonstrate.

Table II - 7

Naturally Occurring and Radiation-Induced Genetic Disorders (National Research Council 1980).

| Type of Disorder | Normal Incidence per $10^6$ Liveborn | Effects per $10^6$ Liveborn per rem per Generation: First Generation | Effects per $10^6$ Liveborn per rem per Generation: Equilibrium |
|---|---|---|---|
| Single-Gene Automosal Dominant and Sex Linked | 10,000 | 5 - 65 | 40 - 200 |
| Irregularly Inherited | 90,000 | - | 20 - 900 |
| Chromosome Abberrations | 6,000 | < 10 | slight |

Although the genetic effects of radiation have not been demonstrated in studies of human populations and all of our quantitative information has been derived from laboratory animal studies, genetic risks have been considered to be very important in establishing exposure limits for radiation workers. Reports by the National Research Council and National Academy of Sciences (1956, 1980) indicated that a total dose of 50 rem up to the mean reproductive age of 30 yr was probably acceptable for occupational exposures to radiation. This recommendation is consistent with the age-proration formula for maximum accumulated whole-body dose introduced by the National Council on Radiation Protection (1957);

$$\text{Max. Accumulated Dose} = (N - 18) \times 5 \text{ rem}$$

This formula was based upon long experience with the permissible dose of 0.1 rem/day for which no harm had been detected in workers and further recommendations of the National Council on Radiation Protection (1954). These recommendations are still in effect and the gonads, blood forming organs and the lens of the eye are considered the critical organs for whole body irradiation (National Council on Radiation Protection 1971).

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## SECTION III

## CURRENT RESEARCH ON HEALTH RISKS FROM LOW-LEVEL RADIATION EXPOSURES

During the last 70 years, the U. S. government spent about $2 billion on research to determine the potential human health risks from ionizing radiation (U. S. General Accounting Office 1981). The resulting risk estimates form the basis for the federal radiation protection guidelines that apply to radiation workers and to the general public. Most of the information that is currently available to assess radiation health risks comes from epidemiology and laboratory animal studies. Molecular and cellular experiments have aided in understanding some mechanisms of radiation injury and repair, but little direct information for quantitating human health risks may be expected from these types of studies.

Although this research has produced a large body of information on radiation-induced health effects at doses greater than 100 rad, the quantitative magnitudes of risks at lower doses remain uncertain in the opinion of many people. The following discussion reviews ongoing research on radiation health effects to indicate which studies are producing the most quantitative risk information and where new information on health risks at lower radiation doses is likely to be developed. Key references are also provided to guide readers to detailed descriptions of the analyses, results, strengths, weaknesses, and purposes of each study.

### Radiation Epidemiology Studies

Results of human radioepidemiology studies are directly applicable to assessing health risks in other people who have similar exposures, but they also have important limitations. For low-level radiation studies, sample sizes are often inadequate and reliable dosimetry information may be lacking. There may also be incomplete health records, lifestyle information, and medical follow up. Uncertainties in the resulting dose-effect relationships also arise when exposures to natural background and medical radiation, which normally contribute 10 to 20 rem during a person's lifetime, are not taken into account. Because these confounding factors exist in most epidemiology studies, many studies have been undertaken solely to determine if excess health risks have occurred in a population without attempting to derive quantitative dose-effect information. Other studies have been undertaken mainly to demonstrate government responsibility in dealing with public concerns, even when the available data are so limited as to preclude any reasonable expectation of acquiring useful scientific information.

In a recent survey of federally supported research, 88 epidemiology studies are identified related to radiation health effects (Division of Medical Sciences, Assembly of Life Sciences and National Research Council 1981). Twenty-four of these studies are being supported by the Department of Energy, 32 are supported by the National Institutes of Health, and 32 are supported by 8 other agencies. The following summary focuses mainly on studies that are likely to produce radiation dose-effect information suitable for risk evaluation in the low dose range. However, in some cases this expectation is based upon the premise that radiation health risks are being grossly underestimated by current assessments. If this is not the case, then many of the studies will produce little new scientific information.

#### A. Japanese Atomic Bomb Survivors

Irradiation of the Japanese populations of Hiroshima and Nagasaki occurred as a result of detonation of two nuclear weapons in August 1945. More than 38 years have now passed, but the related epidemiology studies are likely to continue for another 30 years or more before completion. However, that portion of the Japanese life span study which is most important for evaluating occupational exposure guidelines and risks will be complete within 15 years, because

workers in the United States must be more than 18 years of age before beginning to work in radiation areas. To date, only cancer has been identified as a late mortality effect of the irradiation. This mainly includes leukemia, lymphomas, and cancers of the thyroid, breast, lung, gastrointestinal tract, and urinary tract.

The Japanese life span study cohort includes about 80,000 people (the extended life span study cohort now includes about 109,000 people) who received radiation exposures between 0 and 600 rad (Wakabayashi et al. 1983, Kato and Schull 1982, Beebe et al. 1978). Their radiation doses are being recalculated at present and this may result in significant changes in the estimated doses, especially for exposures to neutrons for people living in Hiroshima. Thus, radiation dose-effect relationships that have been calculated up to now should be considered as preliminary. Through 1978, a total of 23,502 deaths occurred; 180 people died of leukemia; 4,576 people died of other forms of cancer; and 18,746 people died of other causes. Estimates of the spontaneous and radiation-induced cancers shown in Table III-1, indicate that statistically significant numbers of excess cancers are likely to occur in this population to provide radiation risk factors even for exposure levels of less than 100 rad.

Table III-1
Estimated Lifetime Spontaneous and Radiation-Induced Cancer Incidences in Japanese Atomic Bomb Survivors

| | Exposure Group (rad) | | | |
|---|---|---|---|---|
| | 0 | 1 - 99 | 100 - 199 | 200+ |
| Total Number of People | 31,581 | 42,240 | 3,128 | 2,907 |
| Average Dose to Whole Body (rad) | 0 | 15 | 125 | 300 |
| Total Population Dose (rad) | 0 | 634,000 | 390,000 | 870,000 |
| Predicted Spontaneous Cancer Deaths | 6,850 (80)[a] | 7,720 (90) | 615 (25) | 580 (25) |
| Predicted Radiation-Induced Cancers[b] | 0 | 280 | 175 | 390 |

[a]Approximate standard deviation.
[b]Predicted using an assumed lifetime risk factor of $4.5 \times 10^{-4}$ per rad for all cancers.

B. Ankylosing Spondylitis Patients

Ankylosing spondylitis is a disease that causes immobility of the spine. About 14,000 patients were treated with X-rays in the United Kingdom from 1935 to 1954 (Smith and Doll 1978, Court Brown and Doll 1965). An extensive study of cancer risk in this population was begun in 1955 and the medical follow up still continues today. Excess incidences of leukemia, lymphoma, and cancers of the esophagus, stomach, pancreas, lung, and bone have been reported. In contrast, no excess cancers have been found in spondylitis patients who were not given X-ray treatments.

For patients given a single treatment course, the average dose to bone marrow was estimated to be 200 rad, but the spine itself probably received 500 to 700 rad. Abdominal organs were estimated to receive 50 to 100 rad, whereas lung, esophagus, and lymphatic tissue probably received 200 to 300 rad (National Research Council 1980). Up to 1970, 31 leukemias and 397 total cancers were observed among 1,759 patient deaths (Smith and Doll 1978). For the total group of patients, there is likely to be 1,500 spontaneous cancer deaths, and 200 to 800 additional radiation-induced cancers (Table III-2). Thus, it is likely that estimates of radiation cancer risk factors can be derived from these studies, but they will relate to exposures greater than 100 rad for many organs.

Table III-2

Summary of Radiation Exposures and Expected Cancer Incidences in British Ankylosing Spondylitis Patients Given a Single Course of X-Ray Treatments

| | |
|---|---|
| Total Number of People | 14,111<br>(6,200)[a] |
| Average Dose to Whole Body (rad) | 200 |
| Total Population Dose (rad) | 2,800,000<br>(1,200,000)[a] |
| Predicted Spontaneous Cancer Deaths | 1500 ± 40 (all cancers)<br>40 ± 6 (leukemia) |
| Predicted Radiation-Induced Cancers | 200-800 (all cancers)<br>100-200 (leukemia) |

[a]Numbers in parentheses refer to patients remaining for long-term follow up after removing patients who received a second course of X-ray treatments.

C. Hanford Nuclear Facility Workers

The Hanford Nuclear Facility began operation in 1943 to produce plutonium for the nuclear weapons program. Detailed occupational exposure histories and health records have been maintained for about 30,000 workers since the beginning of the program. These records were analyzed by several investigators, but some findings are controversial and contradictory. Major analyses were reported by Mancuso _et al_. (1977), Gilbert and Marks (1979), Kneale _et al_. (1981), and the U. S. General Accounting Office (1981). All of these analyses have shown a "healthy worker" effect. That is, the Hanford workers are living longer and experiencing fewer cancer deaths than would be expected based upon a comparison with the total U. S. population.

A summary of Hanford worker radiation exposures is given in Table III-3. About 93% of the workers received less than 10 rem of external whole-body radiation. Only 8.5% died prior to 1977 which is the cutoff date for the study by Kneale _et al_. (1981). As can be seen from the predicted spontaneous and radiation-induced cancers in Table III-3, little new information on the

Table III-3

Worker Exposures to External Whole-Body Radiation Between 1944 and 1975 at the Hanford Nuclear Facility and Estimated Cancer Risk

| | Exposure Group (rem) | | | |
|---|---|---|---|---|
| | 0 - 10 | 10 - 20 | 20 - 40 | 40 - 100 |
| Total Number of People | 26,100 | 900 | 730 | 200 |
| Average Dose to Whole Body (rem) | 1.3 | 15 | 30 | 70 |
| Total Population Dose (rem) | 34,000 | 13,500 | 22,000 | 14,000 |
| Predicted Spontaneous Cancer Deaths | 4,700 (± 70)[a] | 160 (± 13) | 130 (± 11) | 35 (± 6) |
| Predicted Radiation-Induced Cancers | 10-30 | 3-12 | 5-20 | 3-12 |

[a]Approximate standard deviations

effects of low doses of radiation is likely to result from these studies unless radiation cancer risks are currently being greatly underestimated. However, these data may ultimately be useful in estimating an upper limit for radiation risk factors in the low dose region and this would serve a very useful purpose for radiation risk evaluations in litigation. Kneale, Mancuso, and Stewart used the Hanford worker data to estimate a doubling dose of 15 rem for induction of radiation sensitive cancers. This and similar results of earlier analyses were criticized by Gilbert and Marks (1979a), Mole (1982), Anderson (1978), Sanders (1978), and Reissland (1978). The analyses of Gilbert and Marks (1979) have not found any relationship between radiation exposures and cancer incidence in Hanford workers except perhaps for multiple myeloma and pancreatic cancer. These types of cancers produced positive correlations with radiation exposure, but they are barely statistically significant and they may also be related to exposures to other harmful agents. Continuing follow up has shown that these correlations may disappear in time (Gilbert and Marks 1980).

D. Naval Shipyard Workers

Excess incidences of leukemia and other cancers have been reported for radiation workers who were employed in building and maintaining nuclear-powered ships at the Portsmouth Naval Shipyard (Najarian and Colton 1978). Because their original study was done using information collected through a telephone survey of workers' relatives and no verification was attempted with medical or occupational records, a follow up review was initiated using job descriptions and radiation records provided by the employer (National Research Council 1980). Contrary to the original publication by Najarian and Colton which reported standard mortality ratios of 5.5 for leukemia and 1.8 for all cancers, the follow up review reported the standard mortality ratios to be 1.5 for leukemia and 1.3 for all cancers.

Another study of Portsmouth Naval Shipyard workers is in progress (Rinsky et al. 1981). A description of worker subgroups and their radiation exposures is given in Table III-4. To date, no excess in leukemia or other cancers have been found, but only 53% of the workers have been followed for more than 15 years post-exposure. The predicted lifetime cancer risk for this population is also given in Table III-4 and indicates that radiation-induced cancers are not likely to be observed in these workers unless radiation risks are currently greatly underestimated.

A second larger study of nuclear shipyard workers has been initiated by the Department of Energy. Records from about 100,000 workers employed at 8 nuclear shipyards over the past 25 years will be studied for total mortality, cancer mortality, and leukemia. Most of the workers received less than 50 rem. Long-term follow up is planned, but the results of this study cannot be expected for several years.

Table III-4

Summary of Radiation Exposures and Estimated Lifetime Cancer Risks for Workers at the Portsmouth Naval Shipyard

| | Exposure Group (rem) | |
|---|---|---|
| | 0 | 0.001 - 100 |
| Total Number of People | 16,930 | 7,615 |
| Average Dose to Whole Body (rem) | 0 | 2.8 |
| Total Population Dose (rem) | 0 | 21,000 |
| Predicted Spontaneous Cancer Deaths | 3,550<br>(60) | 1,600<br>(40) |
| Predicted Spontaneous Leukemia Deaths | 170<br>(13) | 76<br>(9) |
| Predicted Radiation-Induced Cancers | 0 | 5-20 |
| Predicted Radiation-Induced Leukemias | 0 | 1-4 |

E. Workers at Department of Energy Facilities

Epidemiologic studies are being conducted at the Oak Ridge Associated Universities that include about 600,000 persons who were employed by the Department of Energy or its contractors at some time between 1943 and 1985 (Lushbaugh et al. 1983). The studies include about 80 facilities and they will determine if worker health and mortality are affected by exposure to radiation, uranium, or other substances used in nuclear industries. To date, only socioeconomic factors and date of birth have been correlated with mortality from all causes and from cancer. No health effects have been ascribed to radiation or other occupational exposures. The results indicate that there are important confounding factors that are likely to be encountered when attempting to merge occupational health data bases from different facilities to form one large population for the purpose of estimating low level radiation risks.

Other studies of radiation workers in Department of Energy facilities have been described by Wilkinson et al. (1983), Checkoway et al. (1983), and Acquavella et al. (1983). They include workers at the Rocky Flats nuclear weapons facility, Oak Ridge National Laboratory, and Los Alamos National Laboratory, respectively. A summary of workers included in two of these studies and their exposure levels is given in Table III-5. The number of workers in each exposure level is similar for both facilities, but there are large differences in the numbers of unexposed workers or controls. This difference is caused by variations in reporting exposures and the groupings selected for the two studies. No significant radiation effects have been reported to date, although these studies are in their early stages. From the estimated numbers of radiation-induced cancers shown in Table III-5, it does not appear likely that low level radiation effects will be detected in any of the worker populations. Radiation-induced cancer risks would have to be at least 2 to 5 times greater than the highest current estimates of risk in order for excess cancers to be demonstrated in these studies.

Table III-5

Summary of Workers, Radiation Exposures and Lifetime Cancer Risks Included in Two Epidemiologic Studies Being Conducted at Department of Energy Facilities

| | Exposure Levels (rem) | | | |
|---|---|---|---|---|
| | 0 | 0 - 5 | 5 - 10 | 10+ |
| A. Rocky Flats Workers | | | | |
| Total Number of People | 52 | 5,511 | 582 | 633 |
| Predicted Spontaneous Cancer Deaths | 10<br>(3) | 1,100<br>(33) | 116<br>(11) | 127<br>(11) |
| Predicted Radiation-Induced Cancers | 0 | 3-12 | 1-4 | 1-5 |
| B. Oak Ridge Workers | | | | |
| Total Number of People | 2,132 | 5,351 | 337 | 313 |
| Predicted Spontaneous Cancer Deaths | 405<br>(20) | 1,017<br>(30) | 64<br>(8) | 59<br>(8) |
| Predicted Radiation-Induced Cancers | 0 | 3-12 | 1-2 | 1-2 |

F. Uranium Miners

Radiation exposures to uranium miners occur from inhaled radon and its radioactive daughter products. These are short-lived, alpha-emitting radionuclides so that most of the radiation dose is delivered during the period of time the miner is underground. The largest doses are delivered to cells surrounding the tracheobronchial airways which give rise to most of the lung cancers that occur in miners. Exposures to radon also occur in other types of underground mines that are located in areas rich in uranium (i.e., Newfoundland fluorspar mines and Swedish metal mines).

Exposures to radon and its daughter products are measured in working level months. One working level month has been calculated to be equivalent to 0.4 to 0.8 rad (National Research Council 1980). Because the quality factor for alpha radiation is 20, one working level month results in 8 to 16 rem of exposure.

The largest study of lung cancer risk in uranium miners is supported by the U. S. Public Health Service. It includes more than 4,000 miners, some of which received radiation doses to lung tissues exceeding 7,000 rem (Archer et al. 1973, 1976). No excess lung cancers have been detected in groups of individuals exposed to less than 120 working level months (≃ 1,400 rem) although less than 700 miners are in these study groups. The average follow up time is 19 years.

Other major studies of lung cancer risk in uranium miners have been conducted in Czechoslovakia, Canada, and Sweden (National Research Council 1980). The most likely lung cancer risk factor is reported to be between 10 and 50 cases per $10^6$ person years per working level month. However, few miners were exposed to less than 100 rad and it is not likely that low radiation dose-effect information will be developed from these studies.

G. Radium Dial Painters

Most of the radium dial painters are women who ingested radioactive $^{226}Ra$ and $^{228}Ra$ as a result of smoothing the tips of their paint brushes with their lips and tongues (Rowland et al. 1978, 1983). The exposures mainly occurred between 1915 and 1930. A life span study of these workers is in progress that includes 1,468 women, but good measurements of body burdens are available for only about one-half of the worker population. The principal findings are excess incidences of bone sarcomas and carcinomas of the paranasal sinuses. Higher than expected incidences of multiple myeloma may also be occurring, but its relationship to radiation is uncertain (Stebbings et al. 1983).

To date, 42 bone sarcomas have been reported in women with the highest exposures (Table III-6). They received more than 1,000 rad of alpha radiation to bone which is equivalent to more than 20,000 rem. Only about 22% of the total population of dial painters have died, but from the results observed to date, little positive information concerning radiation risk below 100 rad of exposure can be expected.

Table III-6

Estimated Alpha Radiation Doses to Bone of Radium Dial Painters and the Numbers of Bone Sarcomas Observed to Date

| | Exposure Group (estimated rads) | | | |
|---|---|---|---|---|
| | 0 - 5 | 5 - 100 | 100 - 1000 | 1000+ |
| Total Number of People | 672 | 525 | 147 | 124 |
| Average Dose to Bone (rad) | 2 | 20 | 150 | 5,000 |
| Total Population Dose (rad) | 1,350 | 10,500 | 22,050 | 620,000 |
| Sarcomas Observed Among 1,137 Deaths | 0 | 0 | 0 | 42 |

Radiation doses listed in Table III-6 were estimated from information contained in a report by Rowland et al. (1978) because the exposures are only described in terms of μCi of $^{226}Ra$ and $^{228}Ra$ absorbed. This manner of reporting exposures was adopted because of the difficulties in estimating actual doses that gave rise to the bone sarcomas due to uncertainties in the latent period and in knowing how to calculate dose to the affected cells. Bone is a nonhomogenous structure with organized patterns of cells in a calcified matrix. Radium deposited in bone is slowly buried, resorbed, and recirculated. Because of this dynamic metabolism of bone and the short range of alpha particles, it is difficult to estimate time integrated radiation doses to affected bone cells. Unfortunately, expressing exposures in terms of μCi of radium absorbed is a poor indicator of risk and relationships based upon this quantity cannot be used directly in evaluating exposures to other forms of radiation.

H. Exposures to Nuclear Weapons Fallout

Several long-term studies of health effects in populations exposed to radioactive fallout from nuclear weapons tests are in progress. One study includes children who lived in Utah during atmospheric tests conducted at the Nevada Test Site between 1952 and 1958 (Lyon et al. 1979). This study reported a higher incidence of leukemia in children less than 15 years of age between 1951 and 1959 when compared to children born before 1951 or after 1959. Because this effect was higher for children in southern Utah compared to those in northern Utah, it was assumed to be due to exposures to nuclear weapons fallout. However, a recent study by Beck and Krey (1982) indicates that external radiation exposures from fallout throughout Utah probably averaged only 1.2 rem with those in the northern part (1.3 rem) being only slightly higher than those in the southern part (0.9 rem). Because of this and the fact that natural background and medical radiations contribute lifetime exposures greater than 10 rem, it is not likely that cancer incidence patterns in Utah will ever be related to nuclear weapons fallout. [This is discussed in more detail in Section IV of this report.] Nevertheless, additional funding has been provided to expand the original study of leukemia to include all childhood cancers and this expanded study is currently in progress at the University of Utah.

Studies are also continuing of nuclear weapons test participants who received small radiation exposures at the Nevada Test Site. An early study by Caldwell et al. (1980) suggested that there was a statistically significant increase in leukemia among 3,224 men who participated in weapons test Smoky during 1957. These men received an average whole-body exposure of 1 rem. Nine leukemia cases have been observed while only 3.5 were expected up to the time of the study. Because about 1% of all adult males are expected to die from leukemia, this population is likely to experience a total of 32 leukemia deaths. If current radiation leukemia risk projections are correct, less than one radiation-induced leukemia would be expected. Thus, it is not likely that a significant excess in leukemia will be detected in this population resulting from their participation in nuclear weapons tests unless radiation-induced leukemia risk is currently being greatly underestimated. This would be inconsistent with the results obtained in a large number of other studies.

Studies of military participants in nuclear weapons tests are currently being expanded by a National Academy of Sciences committee to include about 40,000 individuals. Using similar calculations as described above, about 400 ± 20 spontaneous leukemia deaths would be expected in this population, whereas only 3 radiation-induced leukemia cases would be expected if their average exposure was 1 rem. Again, this increase is not likely to be detected in an epidemiology study.

I. Medical Exposures to X-Rays

The first widespread use of radiation after its discovery in 1896 was in the diagnosis and treatment of disease. This frequently led to over-exposures of patients and medical personnel who are now the subjects of numerous epidemiologic investigations. The exposures occurred because of a lack of attention to dose measurements and inadequate knowledge of the potential health risks. Thus, current epidemiologic studies of medical radiation exposures are often hampered by unreliable or no exposure information. For example, 16,339 U. S. radiologists and X-ray technicians studied by Matanoski et al. (1975) and 1,377 British radiologists studied by Court Brown and Doll (1958) showed excess incidences of leukemia, lymphoma, multiple myeloma, skin, and pancreatic cancers. In contrast, the 6,560 U. S. Army X-ray technicians studied by Miller and Jablon (1970) showed no radiation effects. Unfortunately, no dosimetry information is available from any of these studies to help interpret the conflicting results or to extend their use in radiation risk analysis.

Several studies have reported increased incidences of leukemia in children of mothers who received diagnostic pelvic X-rays during pregnancy (Bithell and Stewart 1975, Diamond et al. 1973, MacMahon and Hutchison 1964). Although there is much controversy over the effectiveness of prenatal X-rays in causing cancer, the National Research Council Committee on the Biological Effects of Ionizing Radiation (1980) selected a risk factor of 25 fatal leukemia cases per million children per year per rad. This risk factor is about 10 times higher than that derived for irradiation of adults and it appears to last only for the first 10 or 12 years of life. These conclusions are somewhat complicated by studies of Gibson et al. (1968) who showed that adolescent leukemia risk is also influenced by early viral infections and maternal reproductive difficulties. In all of these studies, radiation doses were poorly defined in that they were recorded only in terms of the number of X-ray films taken. Further studies of the potential influences of these problem areas are needed.

Medical X-ray exposures have also been shown to increase the risk of breast cancer in women (Shore et al. 1977, Boice et al. 1978, Myrden and Hiltz 1969). These exposures occurred from repeated fluoroscopic examinations of women who were undergoing treatment for tuberculosis and from X-ray exposures given to women being treated for postpartum mastitis. The study of Shore et al. involved 571 women who received exposures between 40 and 1,200 rad, and experienced 36 breast cancers when only 16 were expected. The study of Boice et al. involved 717 women who received exposures up to 400 rad or more and experienced 41 breast cancers when only 23 were expected. In both studies, statistically significant excess incidences of breast cancer were not detected below 100 rad average exposure. Risk factors for radiation-induced breast cancers were calculated to be from 3 to 10 cancers per million women years per rad of exposure. An average value of 7 cancers per million women years per rad has been recommended for women over 10 years of age (National Research Council 1980).

These studies were able to show a relationship between radiation and breast cancer even with relatively small study populations because (a) breast cancer is about 5 times more sensitive to induction by radiation than most other cancers, (b) adequate radiation dose information was developed, (c) a wide range of doses were used allowing for development of a dose-effect relationship, and (d) the dose-effect relationship appeared to be linear so that low dose extrapolations could be made with relative confidence.

The use of X-rays in treating benign childhood diseases of the head, neck, and chest has also been shown to increase the risk of thyroid cancer (Hempelmann et al. 1975, Maxon et al. 1980, Frohman et al. 1977, Shore et al. 1976, Ron and Modan 1983). Studies of irradiated patients in the United States include almost 8,000 individuals with nearly 120 cases of thyroid cancer, but few of these received less than 100 rad of exposure. A linear dose-effect model was developed

from these data that indicated about 2.5 cancers per million person years per rad. Ron and Modan (1983) studied 10,842 irradiated patients in Israel and derived a risk factor of 14 cancers per million person years per rad. This risk is more than 5 times larger than that derived from studies of U.S. medical patients, suggesting the potential importance of genetic and dietary factors. Several of the studies cited above indicated that females and people under 18 years of age are about twice as sensitive to radiation-induced thyroid cancer as males and people over 18 years, respectively.

In a study of medical patients who received diagnostic administrations of $^{131}I$, no excess thyroid cancers were observed (Holm et al. 1980). The average dose to the 9,643 adult patients was 58 rad and for the 494 adolescent patients the dose was 159 rad. Thyroid cancers have been shown to be induced by radioiodine in Marshall Island residents exposed to nuclear weapons fallout (Conard 1983) and in laboratory rats and mice (Lee et al. 1982, Lindsay et al. 1961, Wallinder et al. 1972). However, radioiodine appears to be only 20 to 30% as effective in inducing thyroid cancer per rad of dose as external X-ray exposure.

Finally, large epidemiologic studies are continuing with patients who were injected with radioactive thorotrast as an X-ray contrast medium used for diagnosing brain disorders and other diseases. This practice began in 1928, but it stopped about 1955 after it was learned that thorotrast caused liver cancer (National Research Council 1980). In studies of German, Danish, and Portuguese patients, at least 300 liver cancers were reported in a total population of about 3,000 individuals who survived for more than 10 years after injection (da Silva Horta et al. 1978, Faber 1978, van Kaick et al. 1978).

Radiation doses to liver in these patients ranged from 100 to several thousand rad, depending upon the amount of thorotrast injected and the survival of each patient. Thus, all of the doses probably exceeded 1,000 rem which accounts for observing liver cancers in about 10% of the thorotrast patients. A risk factor of 13 liver cancers per million person years per rad was calculated from these data for alpha radiation (National Research Council 1980). However, because of the high doses to liver received by the thorotrast patients, it is not known if this result applies to lower doses of radiation.

Laboratory Animal Studies

Toxicology studies using laboratory animals have important advantages and disadvantages compared to epidemiologic studies for use in human risk evaluations. The advantages of laboratory studies include the following: (a) exposures to individuals or groups of animals can be controlled and measured so that doses to critical tissues are generally known within narrow ranges, (b) good and consistent environmental conditions can be maintained so that the role of potential confounding factors is minimized, (c) pathology reporting can be comprehensive, and (d) levels of exposure to toxic substances can be varied and even studied in combination with other related substances to provide dose-effect information and insight into possible mechanisms of injury. The disadvantages of using laboratory animal studies in human risk evaluations lie in the differences between animals and people including (a) physiological differences that may influence exposure patterns and dosimetry, (b) metabolic differences in clearing substances or in repairing injuries, and (c) differences in life spans. All of these factors must be taken into account when extrapolating the results of studies in laboratory animals to project health risk in people.

Laboratory animal and epidemiologic studies encounter a common problem of statistical uncertainty when attempting to estimate risk from low level exposures to radiation. Because health effects occur with very low probability, there are often too few excess cancers in the study population to construct quantitative risk relationships. The minimum number of individuals, N, needed to demonstrate an increased incidence of a health effect in an exposed population is:

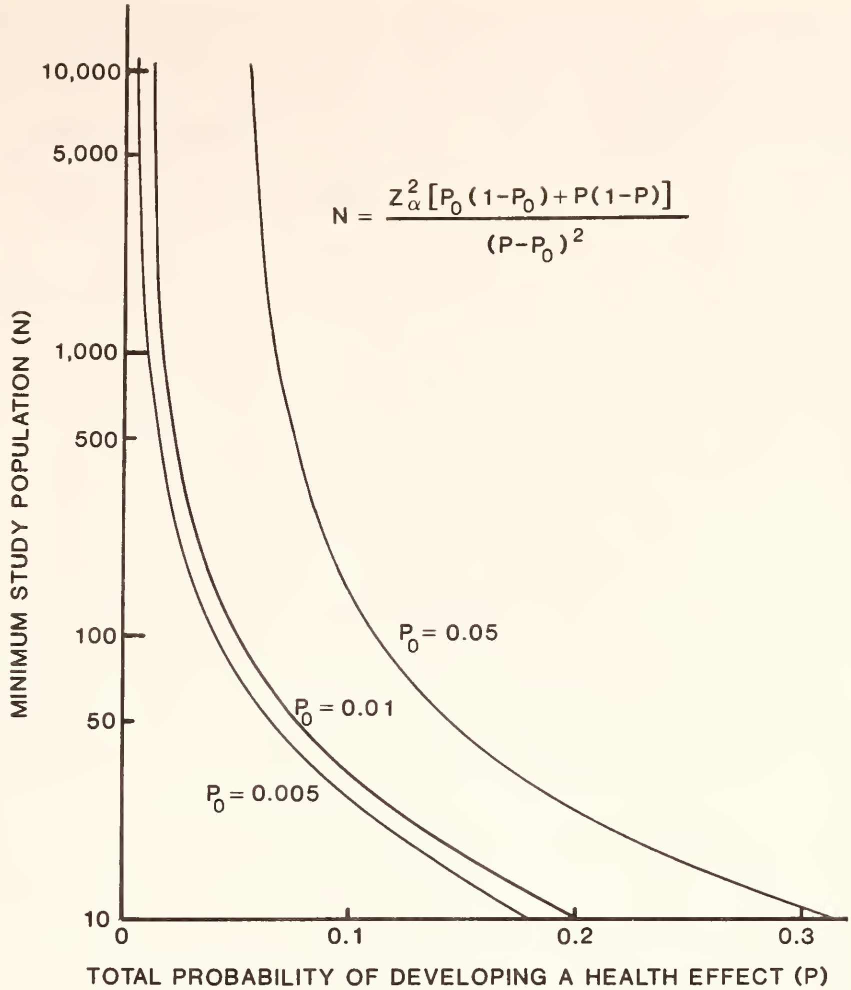


FIGURE III-1. Minimum number of individuals (N) required to detect a statistically significant increase in a health effect in a population with a spontaneous incidence ($P_0$), and a total probability (P) of observing the health effect.

$$N = \frac{Z_\alpha^2[P_0(1-P_0) + P(1-P)]}{(P-P_0)^2}$$

where $Z_\alpha$ is the standard normal deviate ($Z_\alpha$ = 1.65 for a single tailed test at 95% significance), $P_0$ is the fraction of the control population that is expected to develop the health effect spontaneously, and P is the fraction of the exposed population that is expected to develop the effect (Snedecor and Cochran 1967). This relationship is shown graphically in Figure III-1.

Because most laboratory studies of radiation-induced cancer have fewer than 100 animals per exposure group and exposures below 100 rad are expected to have less than 5% excess tumor incidence, this level of effect cannot be detected with statistical significance. Several hundred rad of low LET radiation and more than 50 rad of high LET radiation must be given in such studies to produce quantifiable excess tumor incidences. Several thousand animals must be exposed per experimental group to measure risk from lower doses of radiation. This precludes the use of large laboratory animals (i.e., dogs and primates) on the basis of cost, so that low level radiation risk studies must be done using rodent species.

The larger epidemiology studies described above include tens of thousands of people so that excess incidences of cancer less than 1% may be detected. However, this depends upon the magnitude of the spontaneous incidence rate, $P_o$. As $P_o$ becomes larger, more individuals are needed in the study populations of both animals and people to determine the probabilities of rare effects. Lung cancer in men and breast cancer in women typically have a $P_o = 0.05$. For leukemia and cancers of the large intestine and female reproductive organs $P_o = 0.01$; for cancers of the stomach, pancreas, and liver $P_o = 0.005$.

Two major laboratory studies are in progress that are likely to provide direct measures of cancer risk from low level radiation exposures. One study at Battelle Pacific Northwest Laboratories involves inhalation exposures of several thousand rats to alpha-emitting $^{239}Pu$. The rats will receive as low as 2 rad (equivalent to 20-40 rem) to lung tissue and be observed for their entire life spans. Studies of inhaled beta-emitting radioactivity and external thoracic X-ray irradiation in rats are being conducted at the Lovelace Inhalation Toxicology Research Institute. Exposure groups include several thousand rats that will receive approximately 350 rad and will be observed for life-span cancer risk. A major reason for conducting these studies derives from the concern that low level radiation risks may be underestimated if they are extrapolated from the results of higher level dose studies (Cuddihy 1982). There is still an apparent need to determine the shape of the dose-effect relationship in the critical range of less than 100 rad. Unfortunately, these studies are only addressing lung cancer risk, and other organ risk factors may still need further study in the low dose range. This is especially true for internally deposited radionuclides where information relating to exposed people is almost totally lacking.

The second area of radiation risk assessment where studies with laboratory animals play a vital role is in estimating genetic effects. Well-controlled studies with laboratory animals have demonstrated that ionizing radiation causes transmissible genetic mutations and there is no reason to believe that this would not occur in people. However, genetic effects of radiation have not been quantified in human populations, not even in the Japanese atomic bomb survivors. One reason for this difficulty lies in the high spontaneous incidence of genetic defects which involve about 11% of all live births (National Research Council 1980).

Dominant gene and sex-linked single gene disorders have been related to radiation primarily through studies with mice (Ehling 1966, Selby and Selby 1977 and Ehling et al. 1982). The specific end points were skeletal malformations and eye cataracts. Total genetic risk was estimated by dividing the measured risk by the proportion of all dominant diseases represented by such skeletal and eye disorders. For dominant gene mutations, this was assumed to be between 0.07 and 0.2 which resulted in a risk factor of 5 to 45 cases of dominant gene disorders per $10^6$ liveborn per rem of exposure. For sex-linked recessive diseases, the mutation rate measured in mice was used to derive a human risk factor of 18 per million liveborn per rem of exposure. The risk of radiation-induced chromosome abnormalities was derived based on X-ray-induced translocations in spermagonia of marmosets and humans (Brewen and Preston 1975). After taking account of the impacts of changing dose rate, heritability, and survival of balanced and unbalanced mutations, an estimate of 1 to 10 genetic defects per $10^6$ liveborn per rem of exposure was obtained.

## Prospects for Resolving Radiation Risk Controversies

The need to resolve current controversies concerning the levels of risk associated with exposures to low levels of ionizing radiation increases as occupationally exposed populations grow older. Currently, about 200,000 people work in nuclear industries that have average employee exposures to external penetrating radiation between 200 and 400 mrem/yr. Also, more than 450,000 people work in medical occupations that have similar annual radiation exposure rates. Thus, a

total of 650,000 employees could receive lifetime exposures up to 10 or 20 rem, and about 20% of these or 130,000 employees are expected to develop cancer normally during their lifetimes. Even if no excess cancers due to radiation develop in these populations, a large portion of the naturally occurring cancers could be argued to be caused by occupational exposures in the light of current radiation risk controversies.

A summary of typical radiation exposures to workers in nuclear related industries is shown in Table III-7. The vast majority of individual exposures during 1976 were to less than 1 rem per year and only a few hundred workers received more than 5 rem. Lifetime exposure data are not generally available, except for a few populations that have been subjects of epidemiologic studies. One example is the Hanford workers wherein among 1983 workers that have now died, 112 (5.6%) received lifetime exposures between 5 and 15 rem, and 74 (3.7%) received lifetime exposures greater than 15 rem (Gilbert and Marks 1979). However, occupational exposures among nuclear industry workers have been declining since 1965 (Table III-8). With these changing exposure rates, changing cancer incidence rates, worker mobility, and incomplete medical follow up, it will be difficult to measure radiation risks in all of the worker populations.

The best possibilities for obtaining definitive information on cancer risks from low levels of ionizing radiation lie in completing ongoing epidemiologic studies that have substantial numbers of individuals exposed to less than 100 rad. This includes the Japanese atomic bomb survivors, the Hanford radiation workers, radiation workers at other nuclear facilities, and select groups of medical patients such as those treated with X-rays for ankylosing spondylitis. These studies should be evaluated to provide mathematical dose-effect relationships as well as making specific estimates of the maximum radiation risk factors applicable to the lowest dose groups. Studies for which adequate radiation dosimetry cannot be obtained or long-term follow up is impossible are not likely to help in resolving critical litigation issues.

Adequate human epidemiology studies to quantitate the effects of internally deposited radionuclides or to predict genetic risk for low dose exposures are not likely to be obtained in the future. These questions must be resolved through studies with laboratory animals exposed to doses of less than 200 rad. Such studies will require thousands of animals per exposure group and long-term observations. Because these studies can only be done in rodent species, experiment designs will need to incorporate additional study populations that specifically provide for comparisons to known human exposure risks in order to facilitate extrapolating the results to human exposure situations.

Table III-7

Distributions of Radiation Doses to Workers in Nuclear-Related Industries During 1976 (National Research Council 1980)

| | Department of Energy | Nuclear Regulatory Commission | Shipyard Workers | Nuclear Ship Workers |
|---|---|---|---|---|
| Number of Workers Monitored | 90,200 | 92,773 | 14,669 | 18,229 |
| Average rem Exposure | 0.12 | 0.36 | 0.35 | 0.14 |
| Dose Interval (rem) | Percent of Workers in Dose Interval | | | |
| 0-1 | 97.5 | 88.6 | 87.5 | 97.6 |
| 1-2 | 1.9 | 6.4 | 7.6 | 2.0 |
| 2-3 | 0.53 | 2.9 | 4.1 | 0.31 |
| 3-4 | 0.08 | 1.1 | 0.55 | 0.05 |
| 4-5 | 0.007 | 0.63 | 0.29 | 0.00 |
| >5 | 0.001 | 0.42 | 0.00 | 0.00 |

Table III-8

Distribution of Whole-Body Ionizing Radiation Expsoures for DOE and DOE Contractor Employees, 1965-1980

(U. S. Department of Energy 1982)

| | Dose Equivalent Ranges (rem) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-1[a] | | | | | | | | | | | | | | Total |
| Year | GMeas. | Meas.-1 | 1-2 | 2-3 | 3-4 | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 9-10 | 10-11 | 11-12 | >12 | Monitored |
| 1965 | 128,360 | | 4,158 | 1,704 | 515 | 294 | 70 | 32 | 26 | 25 | 22 | 6 | 2 | | 135,214 |
| 1966 | 131,522 | | 3,706 | 1,630 | 593 | 313 | 88 | 47 | 24 | 6 | 2 | | | 1 | 137,932 |
| 1967 | 102,510 | | 3,472 | 1,572 | 555 | 168 | 35 | 29 | 23 | 17 | 4 | 1 | | | 108,386 |
| 1968 | 103,206 | | 2,799 | 1,408 | 425 | 144 | 3 | 1 | | | | | | | 107,986 |
| 1969 | 98,625 | | 2,554 | 1,313 | 335 | 86 | 4 | | | | | 1 | | | 102,918 |
| 1970 | 92,185 | | 2,698 | 1,329 | 279 | 158 | 5 | 4 | 2 | | 1 | | | | 96.661 |
| 1971 | 90,640 | | 2,380 | 888 | 275 | 118 | 8 | 3 | | | | 1 | | 2 | 94,315 |
| 1972 | 86,077 | | 2,130 | 929 | 219 | 95 | 8 | 2 | | | | | | | 89,460 |
| 1973 | 89,071 | | 1,944 | 727 | 172 | 60 | 2 | 1 | | | | | | | 91,977 |
| 1974 | 43,184 | 32,500 | 1,667 | 688 | 149 | 40 | 4 | | | | | | | | 78,232 |
| 1975 | 43,310 | 42,141 | 1,846 | 753 | 232 | 142 | | | | 1 | | | | | 88,425 |
| 1976 | 40,083 | 47,886 | 1,679 | 475 | 70 | 6 | 1 | | | | | | | | 90,200 |
| 1977 | 43,017 | 49,948 | 1,579 | 545 | 103 | 23 | | | 1 | 2 | | | | 2 | 95,220 |
| 1978 | 44,898 | 55,296 | 1,323 | 439 | 53 | 11 | | | | | | | | | 102,020 |
| 1979 | 50,003 | 53,235 | 1,286 | 416 | 33 | 10 | 1 | | | | | | | 2 | 104,986 |
| 1980 | 45,054 | 38,895 | 1,113 | 387 | 16 | | | | | | | | | | 85,465 |

[a]Separation of data among those employees receiving less than a measurable exposure and those receiving measurable exposures is not possible prior to 1974.

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# CONTINENTAL NUCLEAR WEAPONS TESTS

The first continental nuclear weapon test, Project Trinity, was conducted near Alamogordo, New Mexico, on July 16, 1945. Between 1945 and 1951, United States nuclear weapons tests were conducted at the Pacific Proving Grounds as described in Section V. The Nevada Test Site was developed for continental testing of nuclear weapons in 1951 and continues in use to the present time. Tests of nuclear devices for peaceful uses of atomic energy have been conducted underground at other locations in the United States, but these did not result in significant radiation exposures to people and they will not be discussed here. It is important to note in the following descriptions of nuclear weapons testing in the continental United States and in the Pacific, that few radiation exposures of people occurred to more than 25 R. These are generally considered low level exposures that may only result in small increases in lifetime cancer risk for the more than 200,000 test participants. This is a significant accomplishment in view of the very limited experience with radiological safety prior to 1945 and the unprecedented magnitude of potential radiation hazards associated with nuclear weapons development.

## Project Trinity

The first explosion of a nuclear bomb occurred at the Alamogordo Bombing Range in southern New Mexico. It was conducted by the United States Corps of Engineers, Manhattan Engineer District. The development of nuclear weapons had proceeded along two parallel courses since 1942. One weapon design used highly enriched $^{235}U$ as the fissile material in a ballistic or "gun" type of device, and the other design used $^{239}Pu$ as the fissile material in an implosion type of device. By 1944, scientists in the Manhattan Project were convinced that the "gun" type device would work, but they had serious doubts about the more technically complicated implosion device. They were also concerned that if a device was dropped over enemy territory and failed to explode, the enemy might recover significant quantities of the fissile material. Thus, by March 1944, plans were developed to test a $^{239}Pu$ implosion device.

The Los Alamos Scientific Laboratory formed the X-2 Division within its Explosives Division to conduct the nuclear weapon test. Its duties were "to make preparations for a field test in which blast, earth shock, neutron, and gamma radiations would be studied and complete photographic records made of the explosion and any atmospheric phenomenas connected with the explosion" (LASL 1967).

The name Trinity was chosen for the test by Dr. Robert Oppenheimer and a site in New Mexico was selected after thorough study of eight possible sites. The test site is an area 29 km by 39 km in the northwest corner of the Alamogordo Bombing Range (Figure IV-1). Factors influencing site selection were a remote location with favorable weather and on property already owned by the Federal Government. The Manhattan Engineer District obtained permission to use the site from the Commanding General of the Second Army Air Force.

At the Trinity site, three shelters were constructed about 9 km to the north, west and south of ground zero for personnel and instruments (Figure IV-2). Base camp headquarters was located 16 km southwest of ground zero. Buildings of the abandoned McDonald Ranch, 3.6 km southwest of ground zero, were used to assemble the nuclear weapon.

The organization giving authority to conduct Project Trinity is shown in Figure IV-3. The Los Alamos Scientific Laboratory which was and still is administered by the University of California supervised the field operations. Dr. Kenneth Bainbridge was director of Project Trinity under Dr. Robert Oppenheimer and there were nine scientific and technical advisors organized into the following groups (Maag and Rohrer 1982):

- The Trinity Assembly Group, responsible for assembling and arming the nuclear device

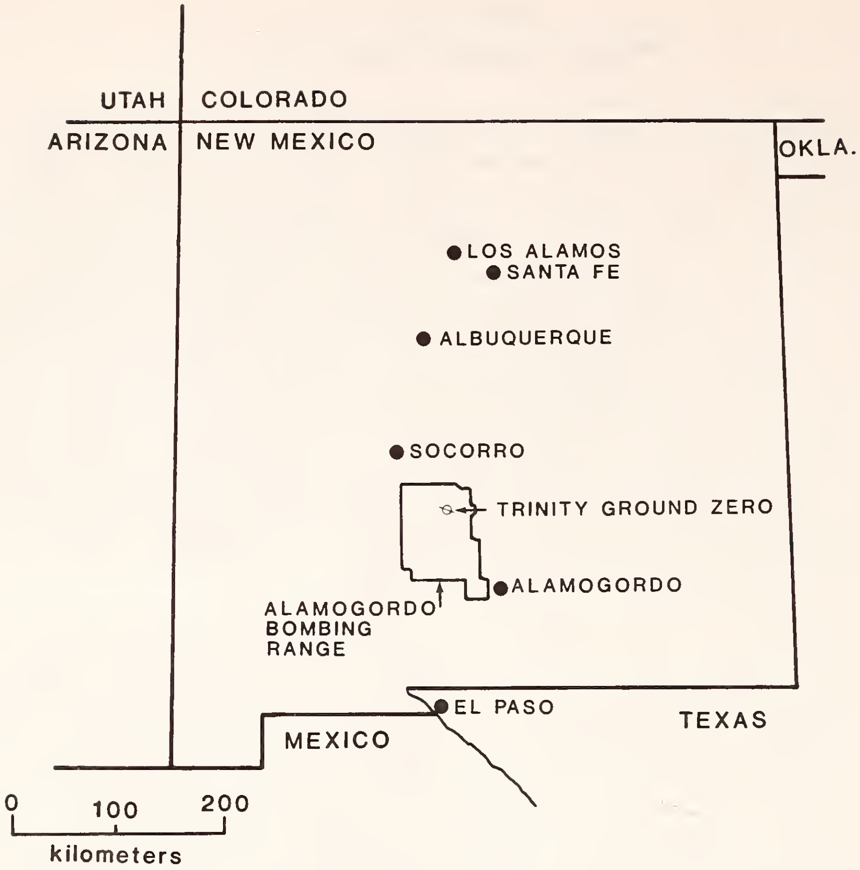


Figure IV-1. Location of the Alamogordo Bombing Range in New Mexico showing the location of the Trinity Site (U.S. Defense Nuclear Agency 1982)

- The TR-1 (Services) Group, responsible for construction, utilities, procurement, transportation, and communications
- The TR-2 Group, responsible for air-blast and earth-shock measurements
- The TR-3 (Physics) Group, responsible for experiments concerning measurements of ionizing radiation
- The TR-4 Group, responsible for meteorology
- The TR-5 Group, responsible for spectrographic and photographic measurements
- The TR-6 Group, responsible for the airblast-airborne condenser gauges
- The TR-7 (Medical) Group, responsble for the radiological safety and general health of the Project Trinity participants.

Above the field operations, Major General Leslie Groves was commanding officer of the Manhattan Engineer District reporting to the Chief of Engineers and the Army Chief of Staff. The Army Chief of Staff reported to the Civilian Cabinet Office of the Secretary of War who reported to the President.

Construction at the Trinity site began in December 1944. On May 7, 1945, a test explosion was conducted using 100 tons of conventional explosives and containers of radioactive fission products obtained from the plutonium production reactors. This test simulated fission product dispersion that was expected from the nuclear explosion. It produced a column of debris 5000 m high, and left a crater 1.5 m deep and 9 m wide. Monitoring of the site indicated that low levels of widely distributed environmental radioactivity were present.

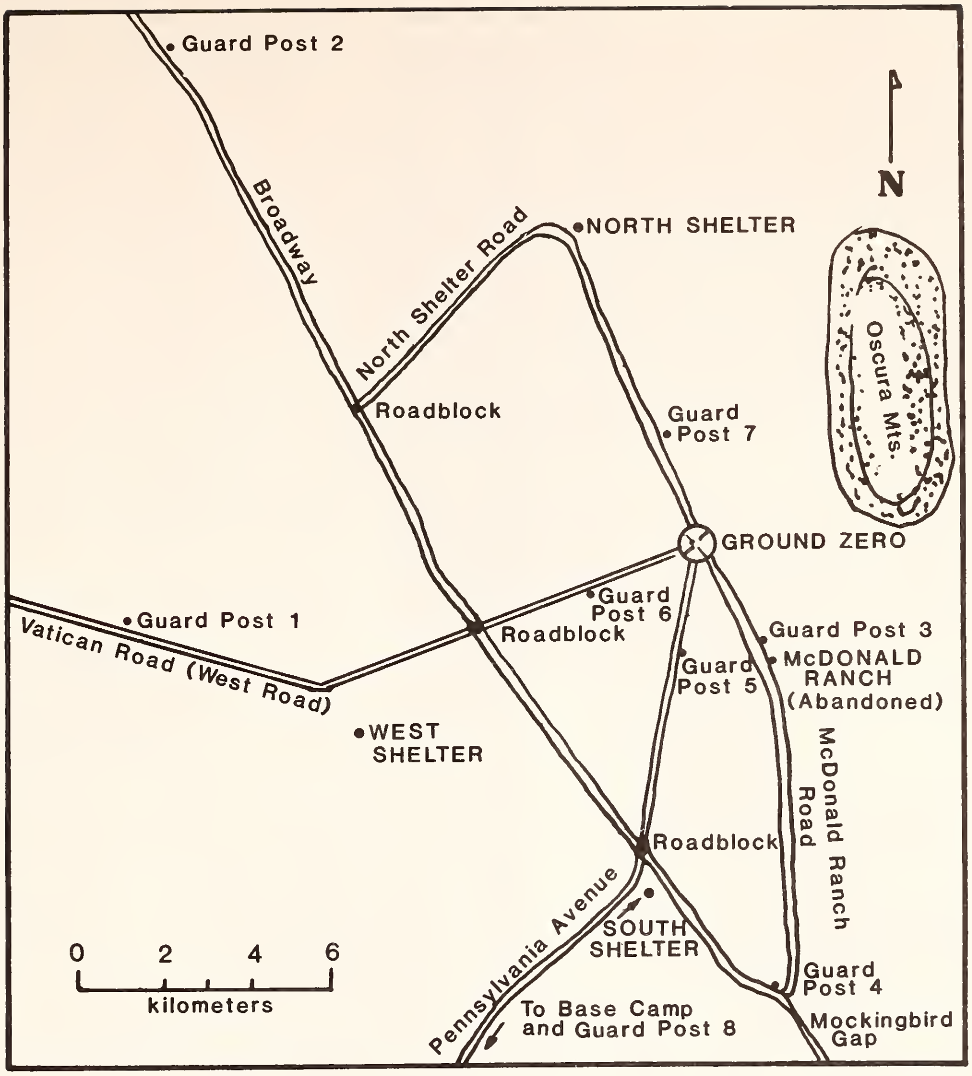


Figure IV-2. Location of Trinity Site and its major supporting installations (U.S. Defense Nuclear Agency 1982).

The Trinity nuclear weapon test was scheduled to precede the Allied Summit Conference at Potsdam, Germany where President Truman hoped to reveal its success to conference leaders. On July 15, 1945, all non-essential personnel left the test site and all essential personnel were assigned to one of the three shelters. At 0100 hours on July 16, military police conducted a sweep of the site to assure that only authorized personnel were in the area. Because of adverse weather conditions, the actual detonation was delayed until 0530 hours. The Trinity device was detonated atop a 30 meter steel tower and the yield was 19 kilotons. No one was closer than 9 km from ground zero. The explosion was visible from as far as Santa Fe and El Paso. Film badge records list 355 people at the test site on July 16; however, most of these were at the Base Camp or at a viewing position on Compaña Hill about 32 km from ground zero. Ninety-nine people were in the shelters.

The Medical Group was responsible for radiological safety during Project Trinity. They maintained radiation detection instruments and protective equipment and clothing, conducted radiation surveys on-site and off-site, and attempted to keep all radiation exposures to a minimum. A two-month exposure limit of 5 roentgens was established for the project.

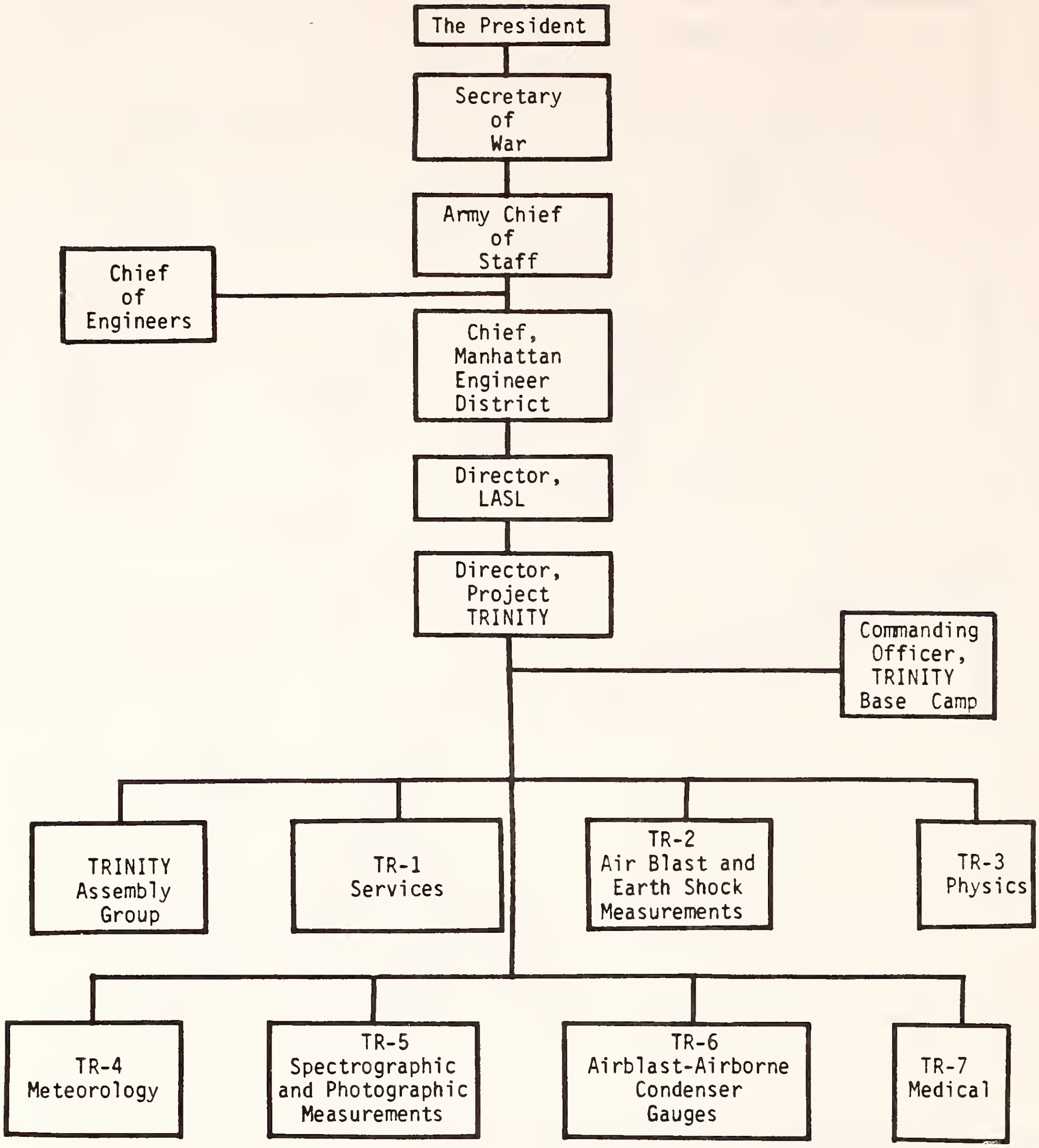


Figure IV-3. Illustration showing the lines of authority for Project Trinity (U.S. Defense Nuclear Agency 1982).

A radiation monitor and a physician with radiological safety training was assigned to each of the three forward shelters during the test. A supervising monitor was stationed at the Base Camp with telephone and radio contact to the forward shelters. Before anyone was allowed to leave the shelter area after the test, monitors equipped with respirators surveyed the evacuation route. It was expected that radioactive dirt from the fallout cloud would fall in one of the shelter areas within 30 min of the test. Therefore, plans had been made to evacuate all shelters as soon as the monitors completed their surveys. Because the cloud moved to the northeast, the south shelter control point was not completely evacuated and a searchlight crew remained in the west shelter for an extended period to follow the fallout cloud as it moved northeast (Aebersold 1947).

Five groups of men were allowed to enter an area near ground zero on the day of the test. A sampling group of eight men approached to within 460 m of ground zero in a military tank equipped with rockets to propel retrievable soil samplers into the ground zero area. Several trips were made toward ground zero on July 16 and 17, but no one received more than 1 R during these activities (Aebersold 1947). A second lead-lined tank carrying a driver and one passenger made five trips into the ground zero area on July 16 and 17. On two trips the tank passed over ground zero, and on two other trips within 90 m of ground zero. Soil samples were scooped up through a trap door in the bottom of the tank. One driver who made three trips received 15 R. Other groups of observers, a photographer and men retrieving neutron monitors traveled near the ground zero area on July 16, but none of these received more than 1 R of radiation exposure (Aebersold 1947). By August 10, roadway blocks were removed and military police patrolled the area at a distance of 730 m from ground zero. Film badges did not record any exposures over 0.1 R from August 10, 1945 to early 1947 when the patrols were stopped.

Radiation Exposure Records for Project Trinity

Film badge records are available for about 700 people who participated in Project Trinity between July 16, 1945 and January 1, 1946 (Aebersold 1947). Based on these records, 23 people received cumulative exposures between 2 and 4 R, and 22 people received cumulative exposures between 4 and 15 R. Thus, less than 6% of all Project Trinity participants were exposed to more than 2 R and these mainly resulted from multiple trips into the ground zero area soon after the weapon detonation. During 1946, about 115 people visited the test site, but no one went inside the perimeter fence surrounding ground zero and no one received over 1 R of exposure.

Four teams of two men and one team of five men constituted the Trinity Off-Site Monitoring Group. Before detonation of the nuclear weapon, the two-man teams established monitoring posts in the New Mexico towns of Nogal, Roswell, Fort Sumner, and Socorro. The five-man team remained at the Trinity site to assist in evacuating nearby residents in the fallout path if necessary. Some evacuation occurred in an area north of ground zero out to 30 km. At Bingham, New Mexico, gamma radiation intensity was 1.5 R/hr between 2 and 4 hours after detonation. South of Bingham, radiation readings ranged up to 15 R/hr, but they decreased to 3.8 R/hr within 5 hr. One month later gamma radiation had decreased to less than 0.032 R/hr. It is noteworthy that significant fallout did not reach the ground within about 20 km of ground zero. The main fallout pattern extended about 160 km to the northeast of ground zero and was about 50 km wide.

The Nevada Nuclear Weapons Test Site

The Nevada Test Site occupies an area of 1,600 $km^2$ in southern Nevada about 150 km northwest of the city of Las Vegas (Figure IV-4). Administrative headquarters for test site operations is at Camp Mercury, which is on the main access road to the technical areas (Figure IV-5). The technical areas are numbered randomly between 1 and 30 and are assigned to different test groups that include scientists and engineers from Los Alamos National Laboratory, Lawrence-Livermore National Laboratory, the Department of Defense, and Sandia National Laboratory. Testing of nuclear weapons at the Nevada Test Site began in 1951, five years after the first nuclear weapon was detonated at Alamogordo, New Mexico (Anders 1983). Two prior nuclear weapons test series were conducted at the Pacific Test Site in the Marshall Islands between 1946 and 1948.

The single most important event that led to the development of the Nevada Test Site stemmed from the Korean War (Hewlett and Duncan 1969). In 1950, Communist China entered the conflict and soon after President Truman declared a national state of emergency. The Pacific Nuclear Weapons Test Site was becoming expensive to operate in terms of military resources and it was also vulnerable to disruption. Therefore, on December 18, 1950, President Truman approved the Atomic Energy Commission's recommendation to establish a continental nuclear weapons test site at the Las


Figure IV-4. Location of the Nevada Test Site in relation to Las Vegas, St. George, Cedar City, and other nearby communities (U.S. Defense Nuclear Agency 1982).

Vegas Bombing and Gunnery Range in Nevada. The first nuclear weapon test was conducted at this site about one month later and, by the end of 1983, about 621 weapons tests were completed (U. S. Department of Energy 1984).

Southern Nevada was selected for the continental test site as a result of an extensive study performed jointly by the Atomic Energy Commission and the Department of Defense (Hewlett and Duncan 1969). The main considerations were to select a relatively remote site that was readily accessible to Los Alamos and suitable for conducting nuclear weapons experiments having low to moderate energy releases. It was also desirable to have a site with regular topography that would be economical to prepare and operate. For radiological safety, it was necessary that local meteorology be favorable and predictable, and that densely populated areas were not located in the direction of the prevailing winds.

In considering the safety of nuclear weapons tests, particular attention has been given to the direction that the wind is likely to blow immediately after detonation. When radioactivity was released to the atmosphere from the Nevada Test Site, it was intended that it would travel toward the north and east and pass over the more sparsely populated areas of eastern Nevada and central Utah rather than over the densely populated areas to the south in Nevada or to the west in California. As a result, some residents of Nevada and Utah were exposed on several occasions to external radiation from fallout clouds and ground surface deposits and to internal radiation principally from radioactive iodine. Several litigations have resulted in which residents of Utah

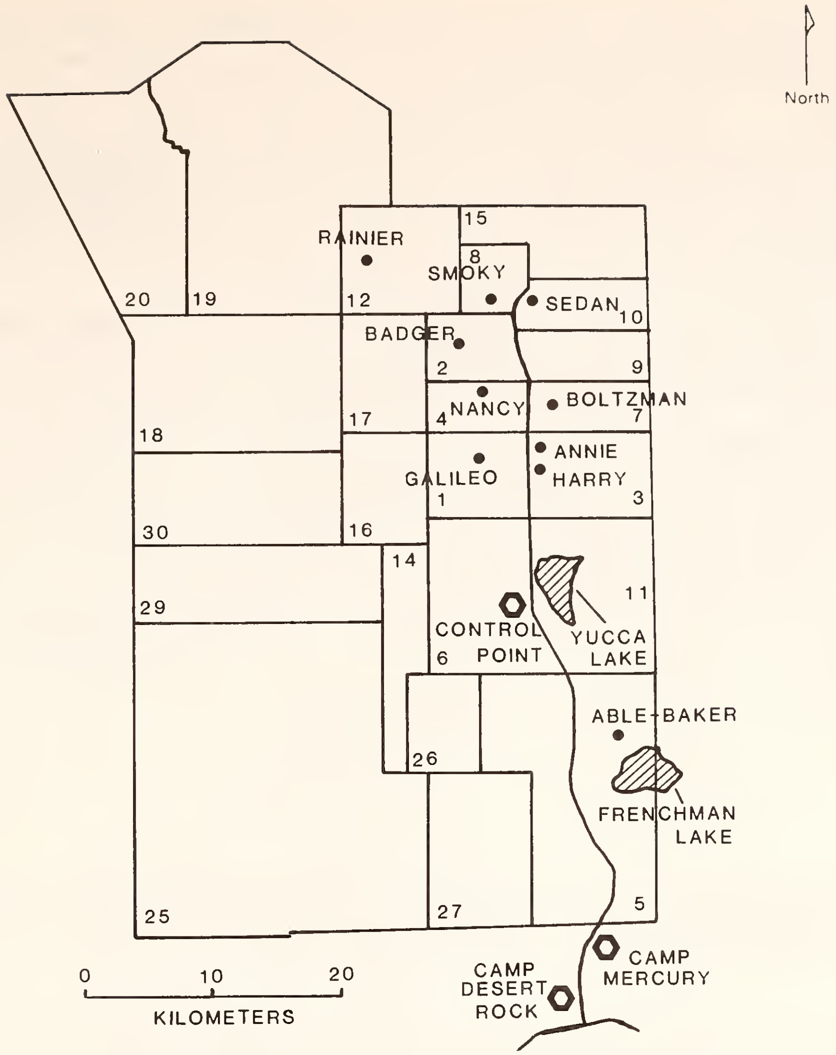


Figure IV-5. Map of the Nevada Test Site showing administrative headquarters at Camp Mercury, the military operations base at Camp Desert Rock, and locations of a few well-publicized nuclear weapons tests (adapted from U.S. Defense Nuclear Agency 1982).

and Nevada alleged that the radiation exposures caused cancers, especially leukemia and thyroid cancer. Another litigation developed from allegations that exposure to fallout resulted in the deaths of about 4,000 sheep that were grazing in southern Nevada during 1953. Still other litigations resulted from radiation exposures to military personnel who participated in conducting the weapons tests.

Authority to Test Nuclear Weapons

Overall authority to develop nuclear weapons and conduct tests is contained in the Atomic Energy Acts of 1946 and 1954 as discussed in the Introduction of this report. Beyond this general authority, there are currently four basic authorities leading to the execution of underground nuclear weapons experiments at the Nevada Test Site. These include programatic authority, detonation authority, permission to move, place and stem (the process by which the test hole is filled with alternate layers of sand and gravel and one cement or plastic plug), and permission to fire (Nevada Operations Office 1983).

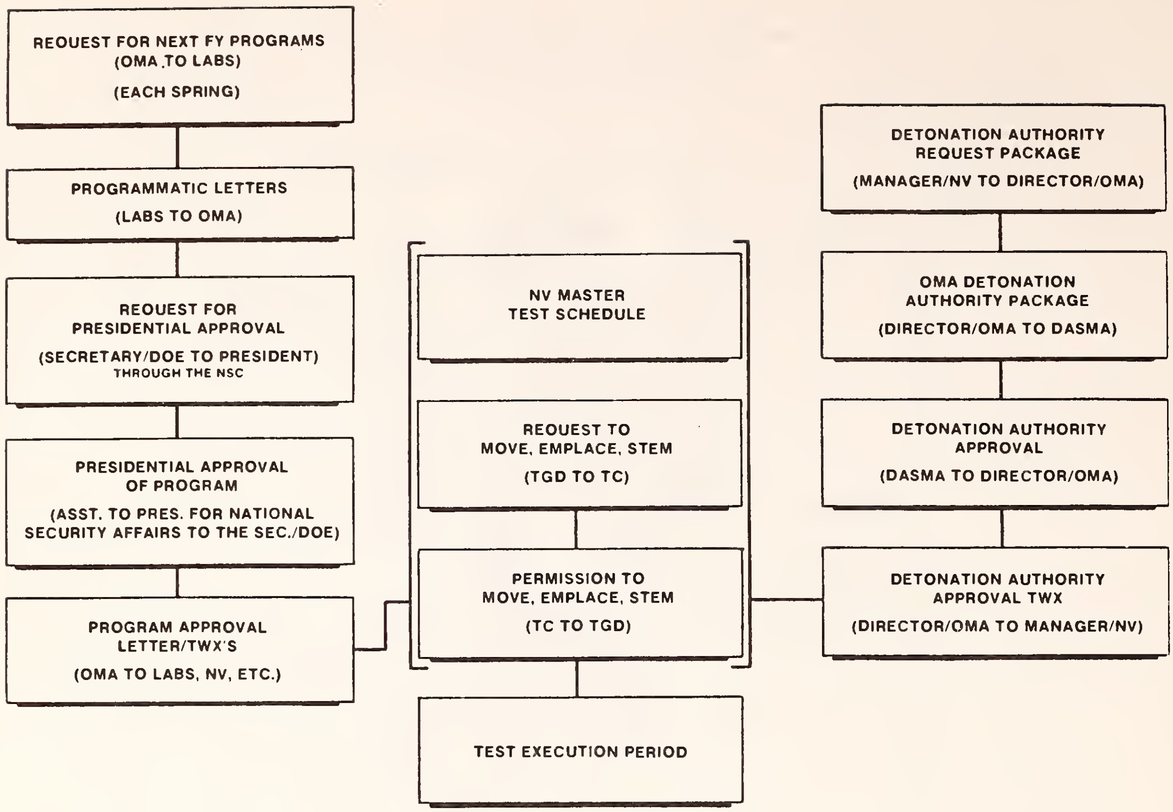


Figure IV-6. Diagram showing current lines of authority for approving nuclear weapons test operations and individual weapon tests (Nevada Operations Office 1983).

The request for programatic authority is initiated each year by the Division of Military Application by requesting the weapons laboratories and the Defense Nuclear Agency to submit proposed test programs for the fiscal year (Figure IV-6). These are consolidated into a single program approval request which is sent by the Secretary of the Department of Energy to the National Security Council. The National Security Council is responsible for obtaining Presidential approval. When concurrence is achieved, test program approval letters are returned to the weapons laboratories, the Defense Nuclear Agency, and the Nevada Operations Office through the same chain of authority.

Detonation authority is obtained for each test by the sponsoring laboratory. This entails submitting a technical request to the Containment and Evaluation Panel. The panel members submit their findings to the Test Manager, who prepares the request for detonation authority and transmits this request to the Department of Energy, Office of Military Application. The Director of Military Application then prepares a final information summary for the Assistant Secretary for Defense Programs. If there is concurrence, then detonation authority is given to the Test Manager returning through the same chain of authority.

Permission to move, place and stem originates with a request from the Test Group Director of the sponsoring laboratory. This is sent to the Test Manager, who assures that all previous safety and containment recommendations have been met in order to permit the nuclear device to be moved and placed. Permission to stem is seldom given unless detonation authority has been received.

The last authority is permission to fire. On the day before a scheduled detonation, separate briefings are given to the Test Controller and his Advisory Panel on the supporting contractors actions, containment as-built, test design, and readiness. Based on these briefings,

the Advisory Panel makes a recommendation and, if favorable, the test execution period begins. Permission to arm the device is given by the Test Controller and permission to fire only depends upon conditions remaining favorable during the final countdown period.

Prior to 1975, the Atomic Energy Commission and the Department of Defense shared the responsibility for planning and conducting the nuclear weapons test program. The Atomic Energy Commission was responsible for developing new areas of nuclear weapons technology. The Department of Defense was responsible for incorporating nuclear weapons technology into the military defense program. Military training programs have operated from Camp Desert Rock located on the Nevada Test Site, but they have been administered by the Army and have functioned separately from the Joint Test Organization. The Joint Test Organization is shown in Figures IV-7 and IV-8 as it existed in 1953 during Operation Upshot-Knothole. Although this Organization has changed since 1953, many of the elements and functions remain today.

The Director of the Atomic Energy Commission, Division of Military Application supervised all nuclear test operations from headquarters in Washington, D.C. The prinicipal Department of Defense agency responsible for developing uses for nuclear weapons was the Armed Forces Special Weapons Project. These activities were coordinated mainly through the Test Manager's Organization. The Test Manager's Organization had an Advisory Panel concerned with safety issues,

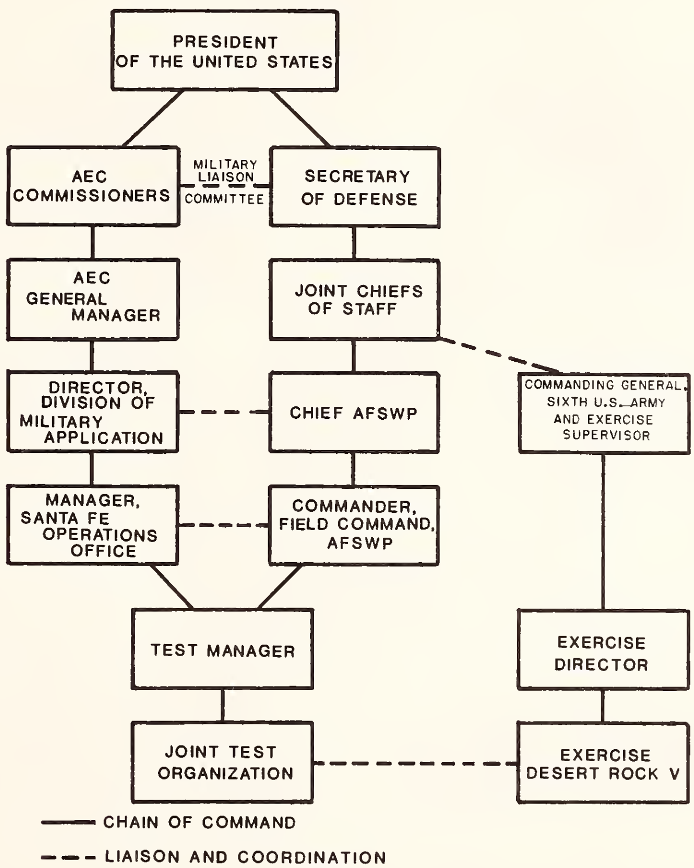


Figure IV-7. Diagram of the Joint Test Organization during Operation Upshot-Knothole in 1953 (U.S. Defense Nuclear Agency 1982d).

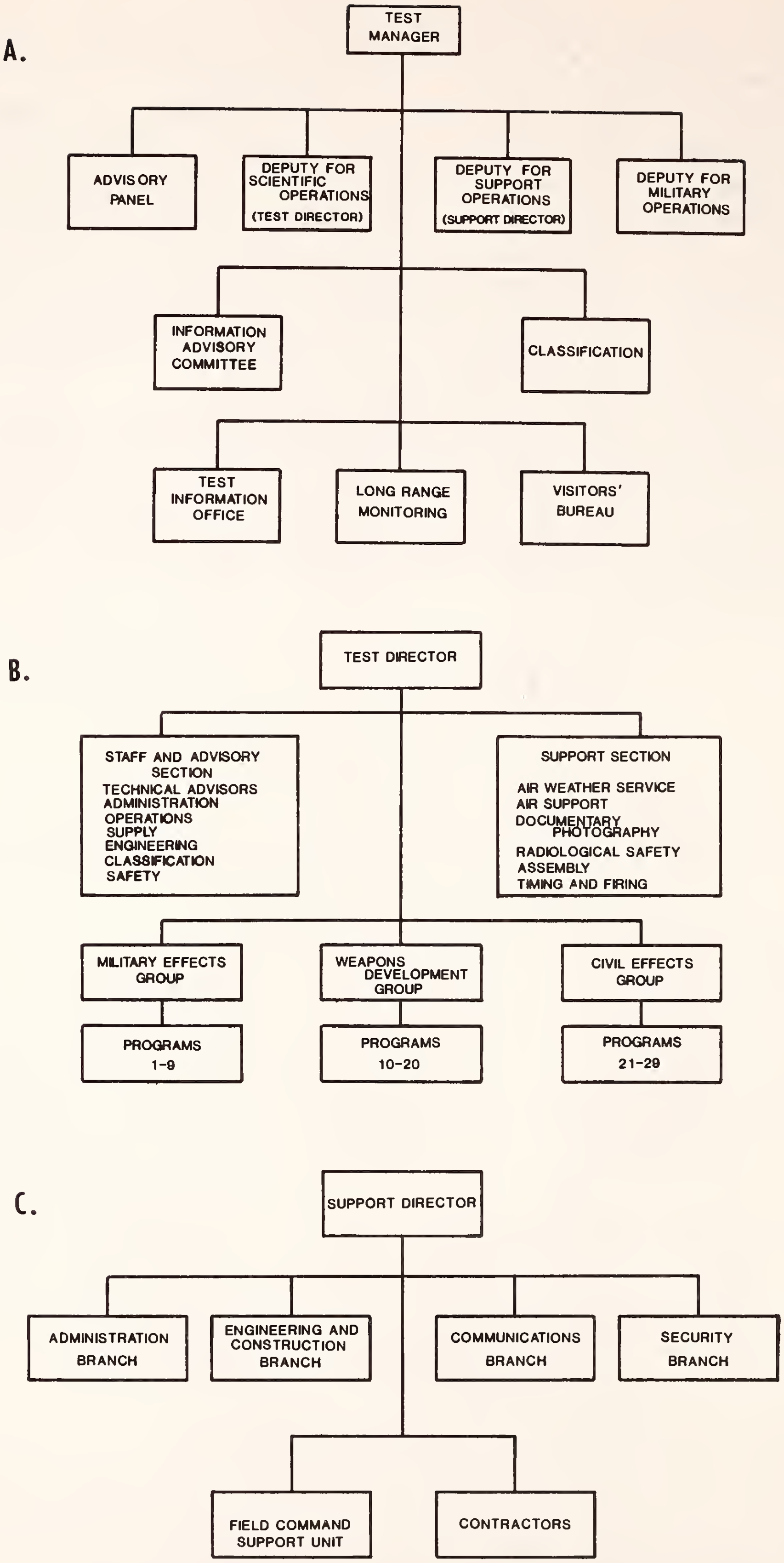


Figure IV-8. Organizations of (A) the Test Manager, (B) the Test Director, and (C) the Support Director during Operation Upshot-Knothole in 1953 (U.S. Defense Nuclear Agency 1982d).

such as the impact of weather on test conditions, and Deputies for Scientific Operations, Support Operations, and Military Operations. Each Deputy had a separate organization as shown in Figure IV-8, indicating their respective functions.

Nuclear Weapons Tests at the Nevada Test Site

Weapons tests at the Nevada Test Site have been conducted in series that have common names such as Operation Ranger or Operation Buster-Jangle (Table IV-1). Single events within a series are also named. Between 1952 and 1958, each test series included events conducted within one calendar year. The unilateral testing moratorium came into effect from November 1, 1958 and lasted until September 1961. Since 1961, each test series has included events conducted within one government fiscal year.

Most weapons tests at the Nevada Test Site have been conducted underground and little radioactivity was released to the atmosphere (U. S. Department of Energy 1984). No weapons tests have been conducted above ground since July 1962. In August of 1963, the United States, Great Britain, and the Soviet Union signed the Limited Nuclear Test Ban Treaty that banned nuclear weapons tests in the oceans, atmosphere, and outer space. However, four cratering experiments were done between 1964 and 1968 as a part of Project Plowshare. Prior to the end of 1962, nuclear weapons tests in Nevada included 20 air drops, 24 balloon, 1 rocket, 41 tower, and 17 surface detonations. These are the most important tests with respect to releases of radioactivity to the atmosphere.

Radiation Safety

The Atomic Energy Commission established radiation safety criteria for each test series and the Test Manager was responsible for all radiation safety programs (U. S. Defense Nuclear Agency 1981a, 1981b, 1982a, 1982b, 1982c, 1982d). Atomic Energy Commission employees assisted in the training and organizing of radiation safety groups for each participating organization, but then each organization was responsible for the safety of its members. Participants at nuclear weapons tests included individuals from the Atomic Energy Commission and its successor agencies, the Department of Defense, other federal agencies, research laboratories, universities, and government contractors.

Off-site radiation safety programs have mainly focused on the area within 320 km of the Nevada Test Site. For the first test series in 1951, these monitoring programs were conducted by employees of the Los Alamos Scientific Laboratory. During the 1952 and 1953 test series, these efforts were assisted by personnel from the military and the Public Health Service (U. S. Department of Health, Education and Welfare 1979). In 1954, a Memorandum of Agreement between the Atomic Energy Commission and the Public Health Service transferred most of the responsibility for off-site radiation safety programs to the Public Health Service and provided for a small permanent staff. These responsibilities were reorganized in 1958 according to recommendations of the National Advisory Committee on Radiation. A Division of Radiation Health was created within the Bureau of State Services, and the role of the Public Health Service was expanded to include monitoring of nationwide fallout, research and training, development of radiation standards, and public information. In 1971, these responsibilities were reassigned to the Environmental Protection Agency, where they have been continued to the present.

A. Sources of Radiation Exposure

Radiation resulting from a nuclear weapon detonation is generally described as either prompt or residual (Glasstone and Dolon 1977). Prompt radiation results from fission or fusion reactions and mainly consists of neutrons and gamma rays. The intensity of these radiations at a particular location depends upon the magnitude of the nuclear reaction and distance. As shown in Figure IV-9, estimated doses to body tissues decrease rapidly with distance such that people who are 3000 m to 5000 m from the center of the blast receive only a few rads of dose.

Table IV-1

Announced Nuclear Weapons Tests Conducted at the Nevada Test Site Between 1951 and 1983

(U. S. Department of Energy 1984)

| Year | Operation | Number of Tests | | | | | |
|---|---|---|---|---|---|---|---|
| | | Airdrop | Tower | Surface | Crater | Shaft | Tunnel |
| 1951 | Ranger | 5 | - | - | - | - | - |
| 1951 | Buster-Jangle | 4 | 1 | 1 | 1 | - | - |
| 1952 | Tumbler-Snapper | 4 | 4 | - | - | - | - |
| 1953 | Upshot-Knothole | 4 | 7 | - | - | - | - |
| 1955 | Teapot | 3 | 10 | - | 1 | - | - |
| 1955 | Project 56 | - | - | 4 | - | - | - |
| 1957 | Plumbob | 14[a] | 9 | 2 | - | 2 | 3 |
| 1957 | Project 57, 58, 58A | - | - | 2 | - | 1 | 1 |
| 1958 | Hardtack II | 11[b] | 9 | 3 | - | 6 | 7 |
| 1961-62 | Nougat | - | - | - | 1 | 38 | 6 |
| 1962-63 | Storax | - | 1 | 5 | 2 | 45 | 2 |
| 1963-64 | Niblick | - | - | - | - | 27 | - |
| 1964-65 | Whetstone | - | - | - | 1 | 32 | 2 |
| 1965-66 | Flintlock | - | - | - | - | 37 | 3 |
| 1966-67 | Latchkey | - | - | - | - | 26 | 1 |
| 1967-68 | Crosstie | - | - | - | 2 | 26 | 2 |
| 1968-69 | Bowline | - | - | - | 1 | 22 | 3 |
| 1969-70 | Mandrel | - | - | - | - | 37 | 5 |
| 1970-71 | Emery | - | - | - | - | 9 | 1 |
| 1971-72 | Grommet | - | - | - | - | 9 | 2 |
| 1972-73 | Toggle | - | - | - | - | 8 | 2 |
| 1973-74 | Arbor | - | - | - | - | 3 | 2 |
| 1974-75 | Bedrock | - | - | - | - | 13 | 2 |
| 1975-76 | Anvil | - | - | - | - | 16 | 2 |
| 1976-77 | Fulcrum | - | - | - | - | 11 | - |
| 1977-78 | Cresset | - | - | - | - | 14 | 2 |
| 1978-79 | Quicksilver | - | - | - | - | 16 | - |
| 1979-80 | Tinderbox | - | - | - | - | 15 | - |
| 1980-81 | Guardian | - | - | - | - | 15 | 1 |
| 1981-82 | Praetorian | - | - | - | - | 20 | 2 |
| 1982-83 | Phalanx | - | - | - | - | 14 | 2 |

[a]Balloon 13; Rocket 1.

[b]Balloon 11.

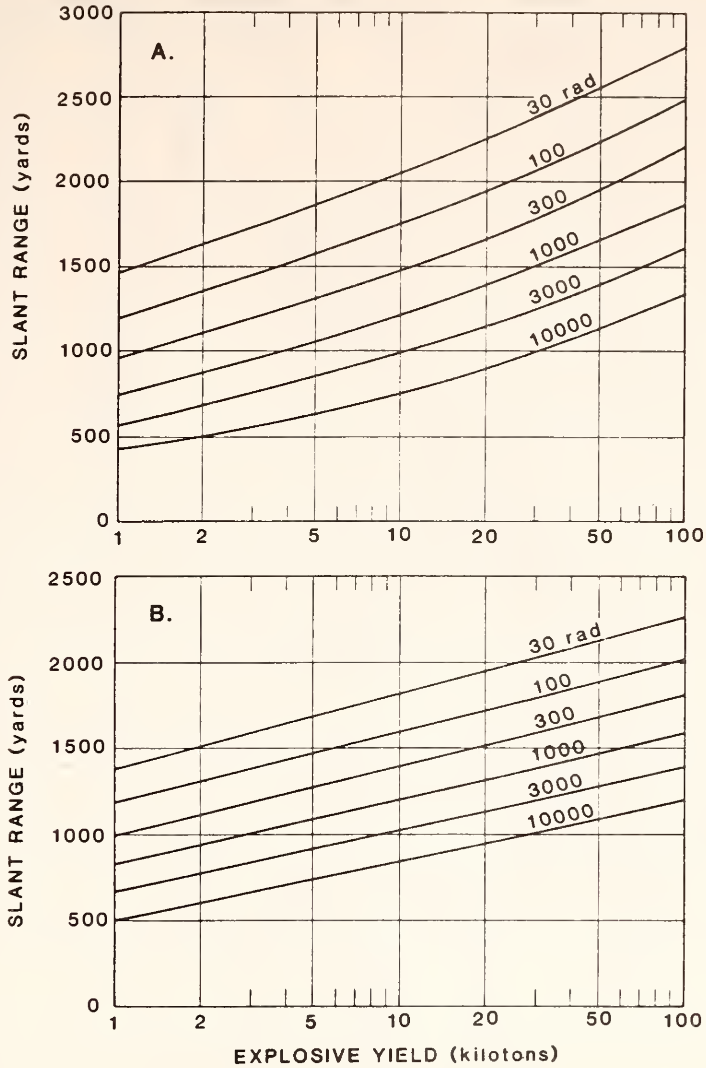


Figure IV-9. Gamma (A) and neutron (B) radiation doses to people related to nuclear weapon yields and distances from air-burst detonations (Glasstone and Dolan 1977).

Residual radiation results from radioactive decay of fission, fusion, and neutron activation products produced by the nuclear detonation. These radiations expose people all along the path of the fallout cloud which eventually becomes global in scale. Several hundred radioactive isotopes are present in fallout, Figure IV-10. However, because they emit different types of radiations and they decay with half-lives ranging from fractions of a second to thousands of years, they are not all equally important in human radiation exposures. The external radiation dose rate at a point distant from a nuclear weapons detonation increases as a fallout cloud approaches, reaches a maximum and then decays (Figure IV-11). The decay rate has been described by empirical mathematical functions of the form (Hicks 1982);

$$\text{Dose Rate}_t = \text{Dose Rate}_{Max}\ t^{-1.2}$$

where Dose $\text{Rate}_{Max}$ is the maximum dose rate measured at a particular location and t is time in hr, or

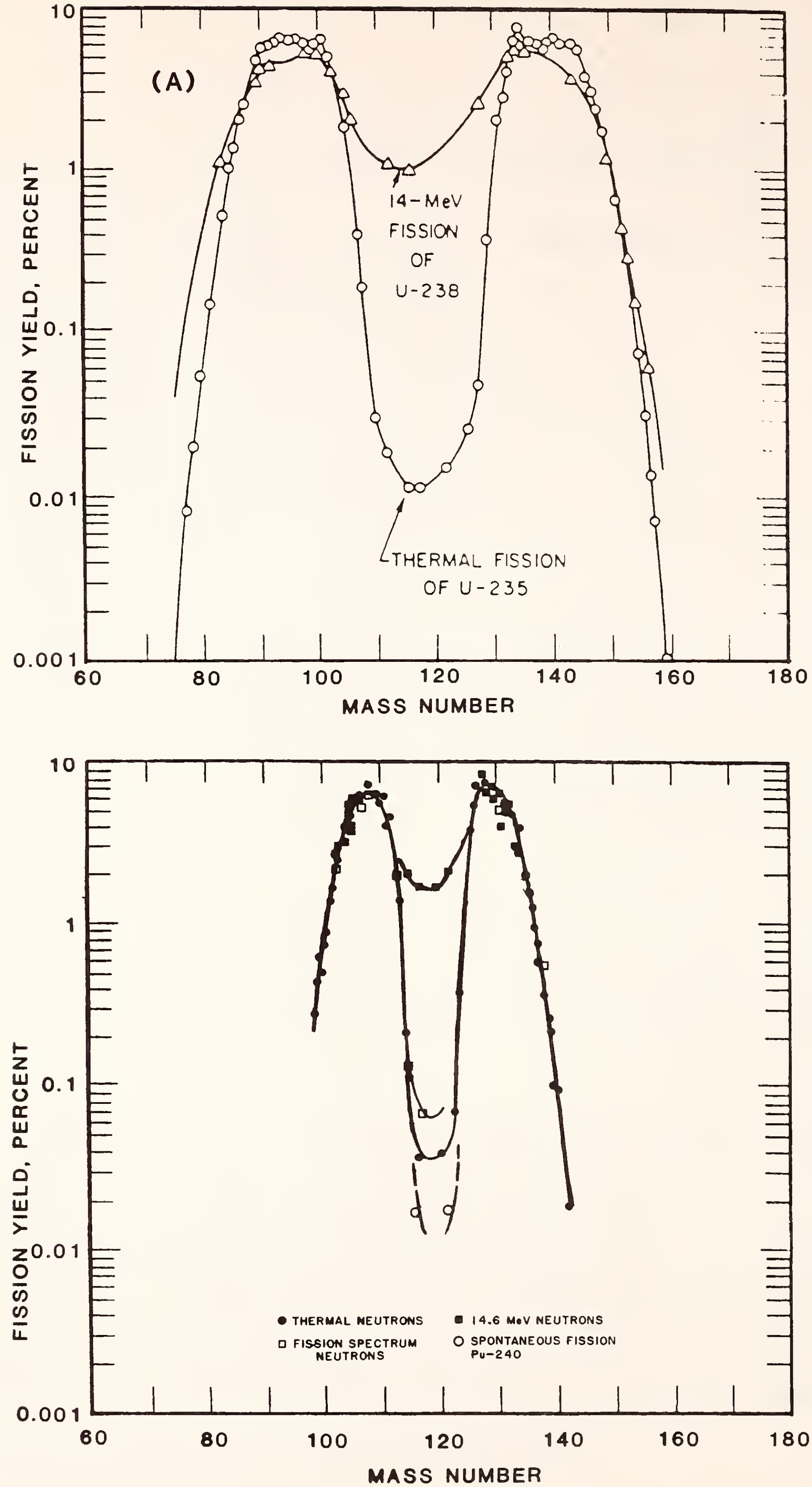


Figure IV-10. Fission product yields related to mass number and neutron energy for fission of (A) $^{235}U$ and (B) $^{239}Pu$ and $^{240}Pu$ (Katcoff 1960).

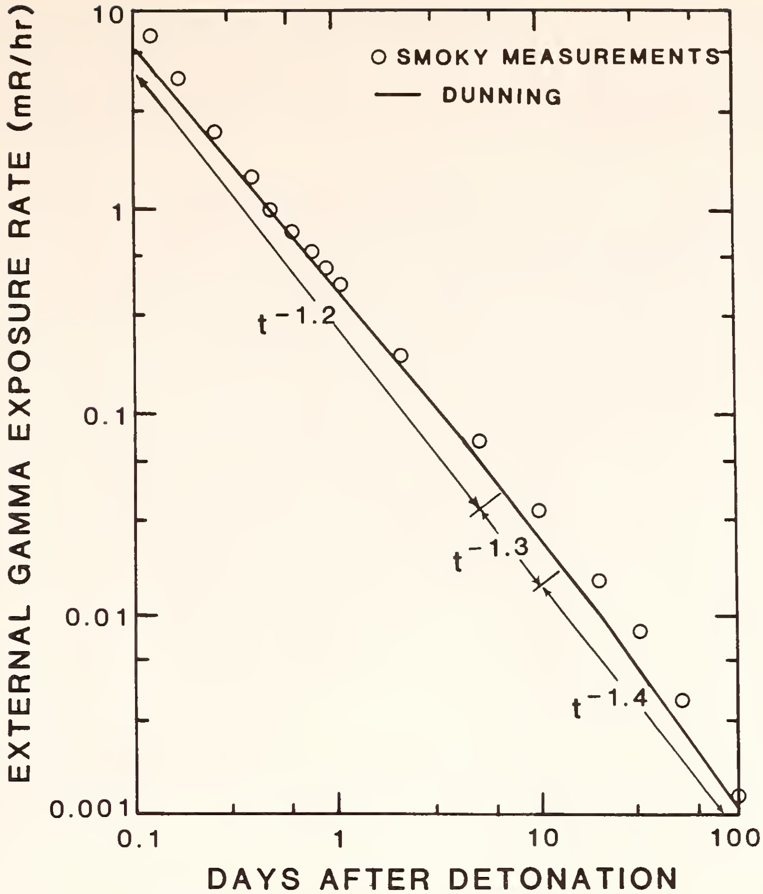


Figure IV-11. External gamma exposure rate calculated for Shot Smoky by Dunning (1958).

$$\text{Dose Rate}_t = \text{Dose Rate}_{Max} \sum_{i=1}^{n} a_i e^{-\lambda_i t}$$

where $a_i$ and $\lambda_i$ are computer fit empirical constants representing fractions of the total external dose rate and their approximate decay rates, respectively.

Depending upon distance from the blast, very short-lived radionuclides may decay before the fallout cloud reaches a given site and very long-lived radionuclides may contribute little to the external radiation because of their infrequent radioactive emissions.

Similar considerations apply to radiation exposures derived from fallout particles depositing on ground surfaces near people or even on their skin. The amount and type of radiation present, its decay rate, and the length of time that the exposure occurs are all important factors. For ingested or inhaled radionuclides, the amount of a radionuclide absorbed, its retention time, and the organ deposition pattern determine the radiation doses that individual organs receive and the likely biological effects. The most important radionuclides in fallout for internal deposition are isotopes of iodine, strontium, and cesium. All are readily absorbed from food and they mainly irradiate the thyroid, bone, and total body, respectively. Their half-lives range from a few days to 30 years.

B. Radiation Monitoring and Data Base Management

A variety of different instruments and measurement techniques were used to monitor environmental radiation levels, doses to individuals, and fallout radionuclide concentrations

after nuclear weapons tests (U. S. Defense Nuclear Agency 1981a through 1982d). Even to the present time, new techniques are being developed to estimate the total fallout in areas near the Nevada Test Site that mainly occurred 20 to 30 years ago (Beck and Krey 1982). However, the present discussion will focus on measurements taken during the early atmospheric test period from 1951 to 1958.

External radiation doses to individuals participating in Test Site operations were mainly monitored with film badges distributed and collected at the Test Site Control Point or at the Indian Springs and Kirtland Air Force Bases. Radiation exposure information obtained from the film badges was subsequently kept at different locations in the United States, depending upon what test organization or military unit an individual was associated with. For military personnel, radiation exposure information was intended to be kept with each individual's service records at a federal repository. In 1955, Reynold's Electrical and Engineering Company assumed responsibility for on-site radiological safety. Beginning in about 1975, a large effort was undertaken to collect the available dosimetry records for nuclear test participants at all test operations from 1945 to the present. The task of obtaining exposure information for all individuals participating in nuclear weapons tests was complicated because in many cases only one or two members of a group of people working together at the Test Site were given film badge dosimeters. In situations where there is a total absence of film badge records, radiation exposures have been estimated from information on where individuals were during specific tests and from calculated or measured radiation field intensities in those areas.

Radiation field intensities were measured using ionization chamber survey instruments. In some cases, serial measurements were made at fixed positions while other measurements were made by monitors that moved to different locations following fallout clouds or military maneuvers. Ground vehicles and air craft were used in these surveys both on and off the Test Site. Results of these measurements were subsequently used to map radiation field intensities extending several hundred kilometers from the Test Site and to estimate radiation exposures to people living in nearby Nevada and Utah communities. One example of a fallout radiation map is shown in Figure IV-12.

Although film badge dosimetry and ionization chamber measurements provide the primary data for reconstructing external radiation exposures to people, additional information was obtained using air sampling devices and fallout collection trays. Air samples were taken to determine the physical and chemical characteristics of fallout particles such as their size, shape, and composition. Fallout collection trays provided additional samples of particles for characterization as well as providing estimates of the total concentrations of radioactivity deposited on ground surfaces.

Measurements were also made of the concentrations of fallout radionuclides in soil, water, vegetation, and milk between 1955 and 1972 (U. S. Department of Energy 1980 through 1983b). This information is available from Public Health Service records and it is currently being entered into computer data storage files maintained for the Nevada Operations Office by the Environmental Protection Agency. These data, together with other published reports on fallout radionuclides in the environment, are being used by the Dose Assessment Group to estimate internal depositions of fallout in Utah residents during selected nuclear weapons test series and to estimate their subsequent radiation doses. The Dose Assessment Group is supported by the Department of Energy and is expected to complete these studies within several years.

Data bases maintained by the Environmental Protection Agency contain several million records of radiation measurements and fallout radionuclides. They will not be summarized here

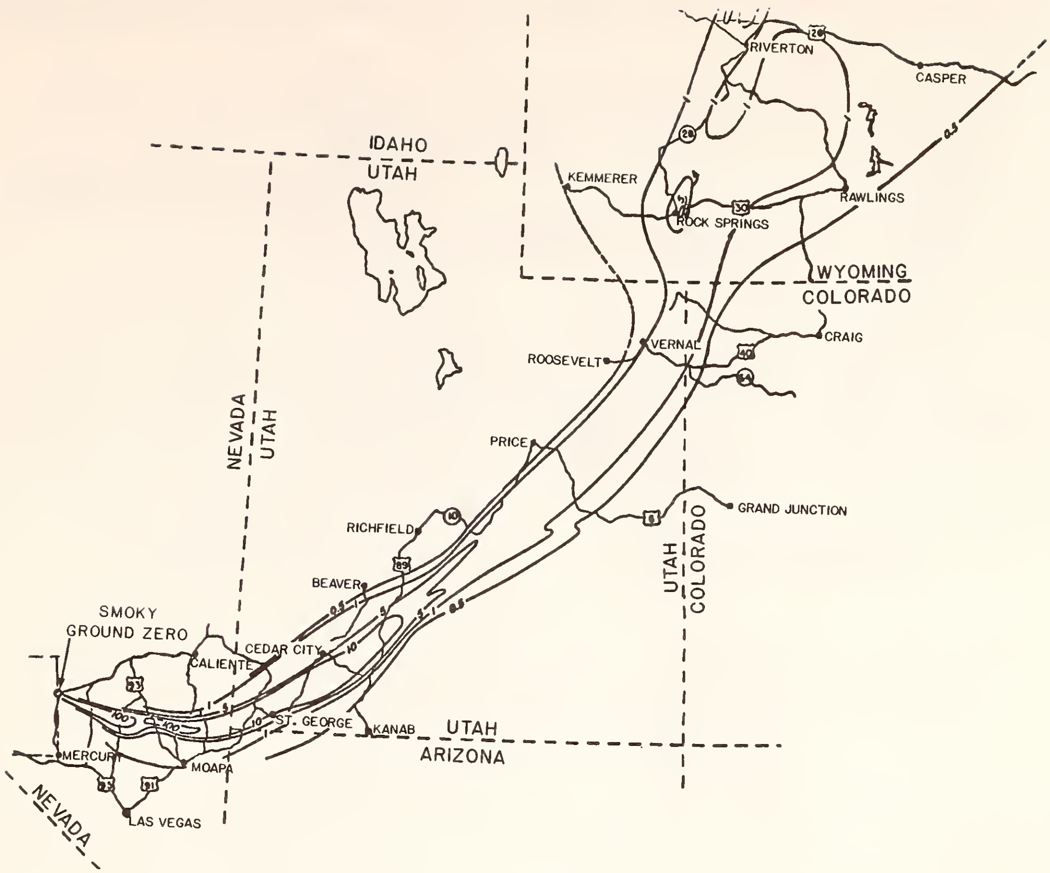


Figure IV-12. Map showing residual surface radiation intensities in mg/hr at 12 hr after detonation of Shot Smoky at 5:30 AM on August 31, 1957 (U.S. Department of Energy 1980-1982).

because they are so numerous, but the general scope of the data bases is illustrated in Figure IV-13. The Historical Dosimetry records indicated are film badge measurements related to off-site locations or people. There is some overlap between the film badge records and records obtained using thermoluminescent dosimeters (TLD). The Sample Tracking Data Management System (STDMS) contains most of the fallout measurements from air, water, soil, plants, and milk.

Studies of residual fallout in Utah are continuing in new attempts to reconstruct radiation doses that were mainly received by area residents during the atmospheric test series. For example, measurements have been made of residual $^{137}Cs$, $^{239}Pu$, and $^{240}Pu$ (Krey and Beck 1981, Beck and Krey 1982). The $^{137}Cs$ measurements are used to estimate the total amount of fallout that deposited in different areas, and the $^{240}Pu/^{239}Pu$ ratios are used to estimate the fractions that originated from weapons tests at the Nevada Test Site. This information is then used to calculate total radiation exposures for people who lived at different locations throughout Utah during different weapons tests.

Radiation Exposures to On-Site Personnel

External radiation exposures to on-site personnel are being evaluated and summarized by the Nuclear Test Personnel Review program established by the U. S Defense Nuclear Agency (1981a through 1982d). The primary sources of exposure information are (a) the historical files of the Reynolds Electrical and Engineering Company which has been a prime support contractor at the

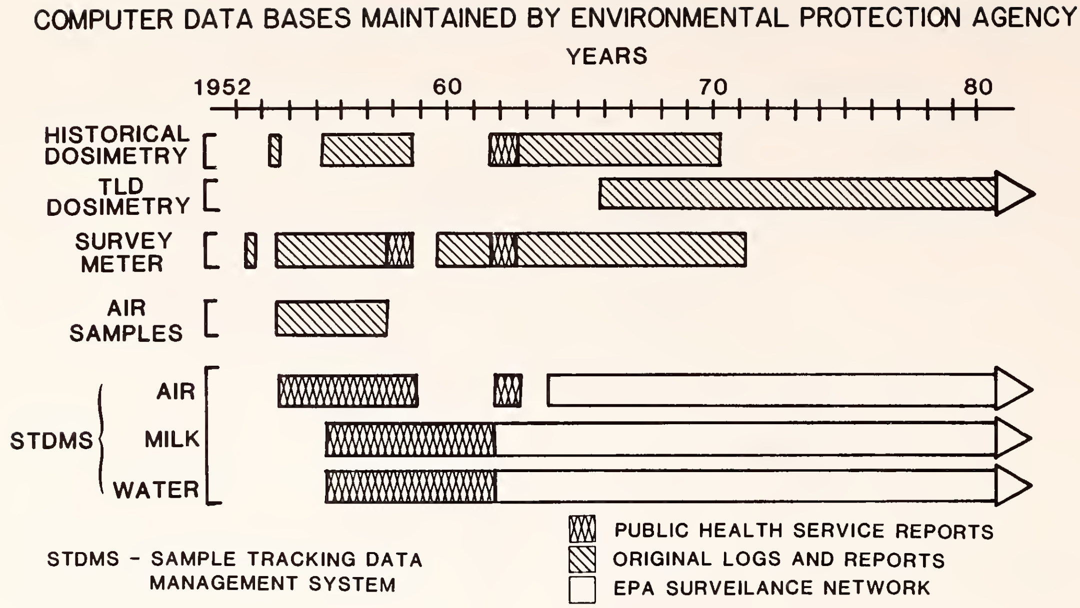


Figure IV-13. Outline of computer data bases being developed by the United States Environmental Protection Agency and maintained at Las Vegas, Nevada available for public use (U.S. Department of Energy 1980-1983).

Nevada Test Site since 1952, (b) military medical records maintained at the National Personnel Records Center in St. Louis, (c) operational radiological safety reports, and (d) the Air Force Special Weapons Command Radiological Safety Group. Exposure summaries are now available for operations Buster-Jangle, Tumbler-Snapper, Upshot-Knothole, Teapot, and Plumbbob.

Approximately 46,000 personnel are identified as participating in the test series listed above of which 22,828 or about 50% were identified with film badge records. Summaries of these exposures are given in Figure IV-14. The average exposure to military and Atomic Energy Commission personnel during these Nevada test series was 0.5 R; however, about 0.7% (164 of 22,828 participants) exceeded 5 R. A summary of measured exposures to all nuclear test participants compiled to date is shown in Figure IV-15. This includes 232,303 individuals, identified by film badge records, who were at tests conducted at either the Nevada or Pacific Test Sites. Again, their average exposure was 0.5 R and about 0.6% (1,319 of 232,303 participants) had exposures that exceeded 5 R. These film badge records do not include exposures to prompt neutrons. Potential neutron exposures to on-site personnel are being evaluated at the present time; however, they are expected to be a small fraction of the total exposures because neutron fluxes decrease rapidly with distance from the center of the blast.

Radiation exposures to on-site military personnel from internally deposited radionuclides are also thought to be small in relation to external radiation exposures. Although few bioassay measurements were made during the weapons test series, if significant internal depositions had occurred from inhaling or ingesting fallout dust, some longer-lived radionuclides would remain in the bodies of test participants even today. For example, $^{90}Sr$ has a long retention time in the body and can be used to estimate previous individual exposures by measuring the amounts that remain in bone by external counting or by measuring its excretion in urine. When measurements were made on a group of 16 military participants at the Smoky nuclear weapon test, no increased retention or excretion of radionuclides was observed compared to control subjects (Toohey _et al._ 1981). Thus, radiation doses to these participants from inhaled and ingested fallout

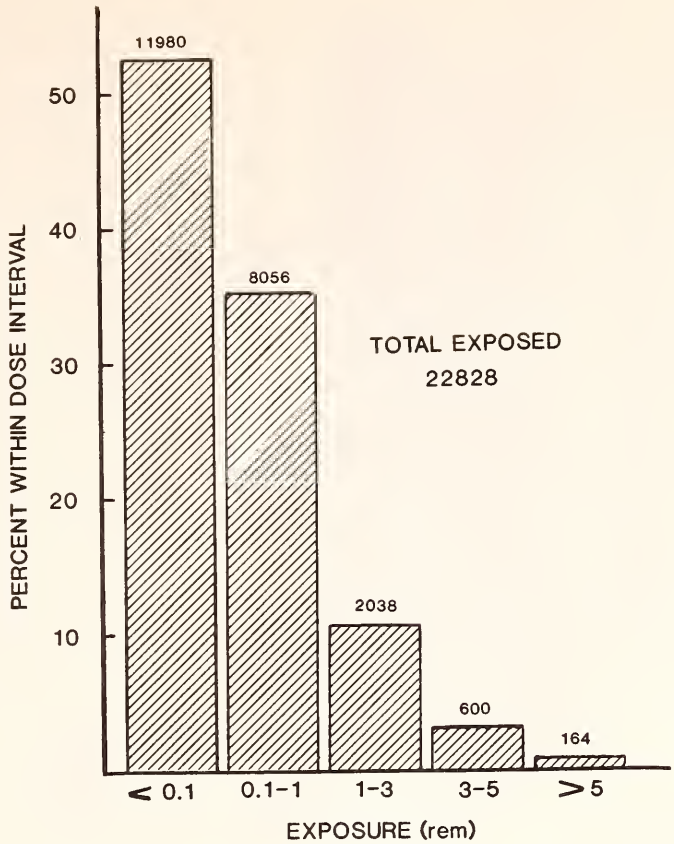


Figure IV-14. Histogram showing external radiation exposures for participants in nuclear weapons tests at the Nevada Test Site during 1951, 1952, 1953, 1955, and 1957 (U.S. Defense Nuclear Agency 1983).

radionuclides could not have greatly differed from doses received by the general public. These have been estimated to be from 50 to 200 mrad to internal organs from internally deposited radionuclides resulting from all weapons tests (United Nations Scientific Committee on the Effects of Ionizing Radiation 1977), although thyroid doses were considerably higher near the Test Site.

<u>Radiation Exposures to Off-Site Populations</u>

Exposures to off-site populations resulted from external penetrating radiations, internally deposited radionuclides, and radiations with low penetration that exposed only skin. Different types of studies were used to estimate the magnitudes of these exposures for people who lived in Nevada and its bordering states and for people who lived in other areas of the United States. These are discussed separately below.

To estimate radiation exposures to populations that lived near the Nevada Test Site during atmospheric testing, the Department of Energy established the Off-Site Radiation Exposure Review Project in 1979 (U. S. Department of Energy 1981 through 1983). The Nevada Operations Office was given primary responsibility for this project and a Dose Assessment Advisory Board was established pursuant to the Federal Advisory Committee Act (Public Law 92-163). The total effort of this project is expected to take about 5 years. A complex outline of individual tasks to be performed is shown in Figure IV-16. The final goal is to estimate the effective radiation doses to people from external radiation and from inhaled and ingested radionuclides. These are to be estimated,

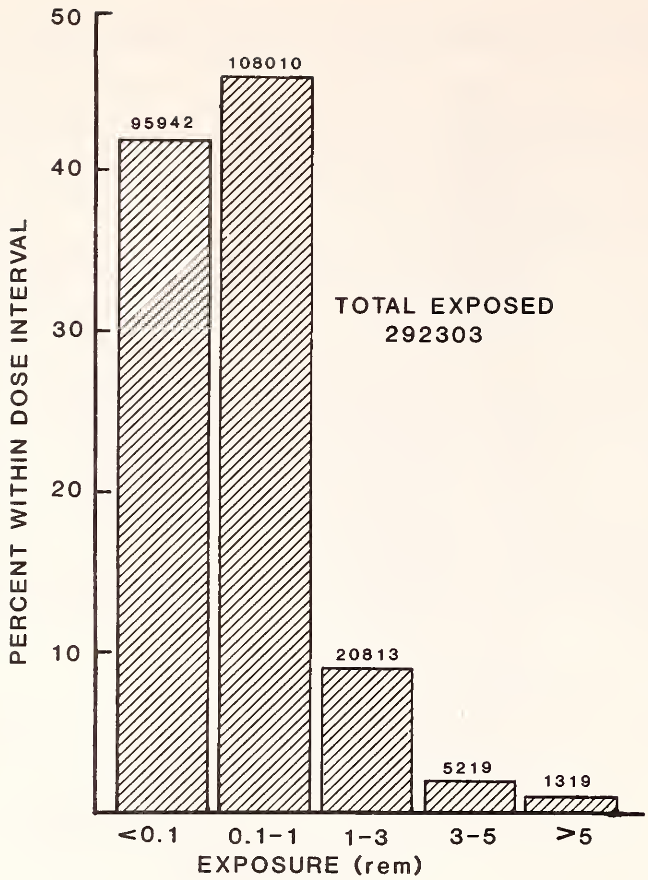


Figure IV-15. Histogram showing external radiation exposures including all military personnel who participated in nuclear weapons tests at the Nevada and Pacific Test Sites (U.S. Defense Nuclear Agency 1983).

based upon previous measurements of radiation in air and radioactivity in air, water, soil and food. Because insufficient data are available to quantitate the human exposures directly, many mathematical modeling studies are also needed. When data are available, model calculations are to be verified and the magnitudes of their uncertainties estimated.

The output of the Off-Site Radiation Review Project will enable scientists to determine which populations received the most significant radiation exposures for such purposes as epidemiologic studies. Radiation exposures to individuals will also be calculated with input information on their date and place of birth, residence history, and lifestyle factors. Such calculations have already been done for litigants involved in radiation injury claims against the Government.

The first major effort to estimate off-site population exposures from nuclear weapons testing was undertaken by the Test Manager's Committee to Establish Fallout Doses (Sheldon et al. 1959, Dunning 1958). Their work focused on the available measurements of radiation intensities in air immediately after a weapon test and on mathematical modeling of the movement of fallout clouds and the deposition of fission products on ground surfaces with increasing distance from the Test Site. Little effort was given to estimating radiation doses from internally deposited radionuclides. Other attempts to reconstruct these exposures are described by Anspaugh and Church (1983). All of these analyses mainly rely on the measurements originally summarized by the Test Managers Committee (Sheldon et al. 1959).

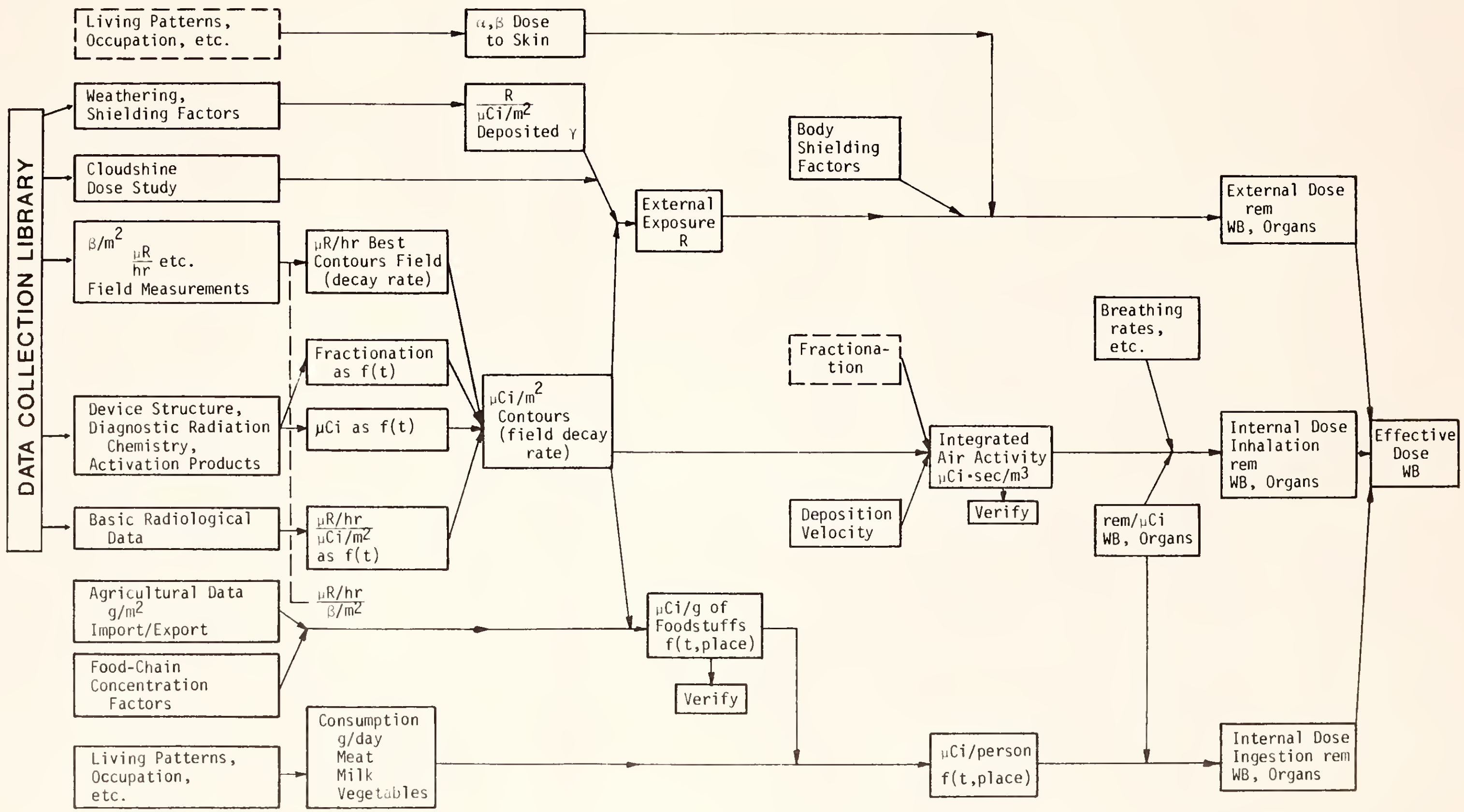


Figure IV-16. Diagram of tasks being performed in the Off-Site Radiation Exposure Review Project to estimate radiation doses to people who lived downwind from the Nevada Test Site during atmospheric nuclear weapons testing (U.S. Department of Energy 1980-1983).

Two types of exposure summaries are reported by Anspaugh and Church (1983) as a part of their work for the Off-Site Radiation Exposure Review Project. The first is the cumulative exposure to the total populations of cities and towns or the entire area within a few hundred miles of the Test Site. The second is the exposure that an individual would receive if he or she remained at a single location throughout the early test series. Both types of exposures are reported in units of R which refer to radiation measurements in air equivalent to roentgen. The ratio of absorbed dose to exposure in R for similar radiation fields was estimated to be 0.7 (Ashton and Spiers 1979). Exposures to off-site populations were estimated for the first year after each event and include a factor of 0.75 to account for shielding by structures such as houses and cars and a factor between 0.7 and 0.83 to account for weathering of fallout into ground surfaces with time.

Cumulative population exposures estimated for test series conducted between 1951 and 1959 are listed in Table IV-2. They include population centers within 300 miles of the Nevada Test Site. About 50% of the total population exposure resulted from the Upshot-Knothole series conducted in 1953, and of this, 75% resulted from fallout released from Shot Harry conducted on May 19. Fallout from Shot Harry traveled eastward and passed almost directly over St. George, Utah (Figure IV-17). Radiation exposures estimated at different locations in Utah, Nevada, Arizona, and California are shown in Table IV-3. These represent cities and towns that experienced the highest population exposures in each state. Calculated exposures to individuals who would have lived at each of these locations for the duration of the test series were as large as 4.3 R. However, single sites in Nevada that had very low populations during the 1950s were estimated to have cumulative exposures up to 15 R.

Beck and Krey (1982) also calculated cumulative radiation exposures to Utah residents using recent measurements of $^{137}Cs$, $^{240}Pu$, and $^{239}Pu$ in undisturbed soil. A comparison of the exposures calculated by Beck and Krey with those reported by Anspaugh and Church is shown in

Table IV-2

Cumulative Radiation Exposures to Populations Living Within 300 Miles of the Nevada Test Site from Nuclear Weapons Tests Conducted Prior to 1959 (Anspaugh and Church 1983)

| Test Series | Year | Cumulative Population Exposure in R |
|---|---|---|
| Buster-Jangle | 1951 | 610 |
| Tumbler-Snapper | 1952 | 4,700 |
| Upshot-Knothole | 1953 | 40,000 |
| Teapot | 1955 | 19,000 |
| Plumbob | 1957 | 11,000 |
| Hardtack II | 1958 | 1,500 |
| Total | | 76,810 |

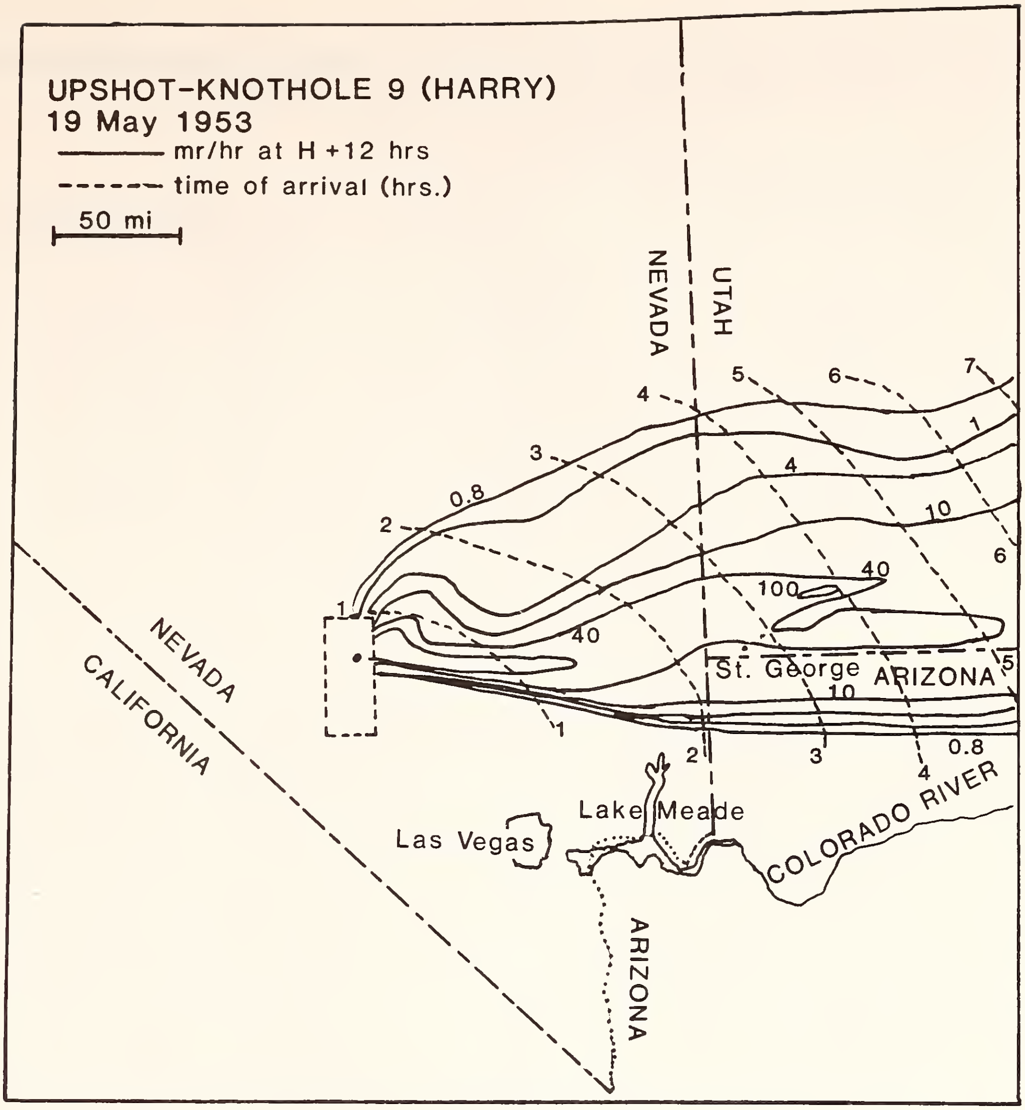


Figure IV-17. Map showing residual surface radiation intensities in mr/hr at 12 hr after detonation of Shot Harry on May 19, 1953 (U.S. Department of Energy 1980-1983).

Table IV-4. All of the comparison measurements agree within a factor of 4 and more than half are within a factor of 2. This agreement adds confidence in the estimates of external radiation exposures to off-site populations.

Relative to the exposures from external radiation sources, exposures resulting from internally deposited radionuclides are poorly known. However, considerable effort is now being directed toward estimating these exposures by the Off-Site Radiation Exposure Review Project (U. S. Department of Energy 1980 through 1983b). This requires information on the amounts of fallout radionuclides that deposited at specific locations off-site and the amounts that were inhaled or ingested by people living nearby. Mathematical models are available to perform the

Table IV-3

Cumulative Radiation Exposures to Individuals and Populations Living in Cities and Towns Near the Nevada Test Site Between 1951 and 1959

(Anspaugh and Church 1983)

| Location | | Population | Cumulate Exposure to Individuals R | Cumulate Exposure to Population Person R |
|---|---|---|---|---|
| Utah: | St. George | 5000 | 3.7 | 18000 |
| | Hurricane | 1375 | 3.5 | 4800 |
| | Cedar City | 6106 | 0.64 | 3900 |
| | Kanab | 1900 | 1.6 | 3100 |
| | Washington | 435 | 3.3 | 1400 |
| | La Verkin | 387 | 3.7 | 1400 |
| | Santa Clara | 319 | 4.3 | 1400 |
| | Panguitch | 1500 | 0.7 | 1000 |
| Nevada: | Las Vegas | 47000 | 0.21 | 9900 |
| | Ely | 3558 | 1.2 | 4300 |
| | Lincoln Mine | 100 to 500 | 6 | 3000 |
| | N. Las Vegas | 13000 | 0.2 | 2600 |
| | McGill | 2300 | 0.77 | 1800 |
| | Tonopah | 1375 | 1.1 | 1500 |
| | Mesquite | 590 | 2.1 | 1200 |
| | East Ely | 1000 | 1.2 | 1200 |
| Arizona: | Kingman | 5500 | 0.04 | 220 |
| | Short Creek | 90 | 1.6 | 140 |
| | Littlefield | 45 | 1.9 | 84 |
| | Mt. Trumbull | 100 | 0.16 | 16 |
| California: | Bishop | 2830 | 0.06 | 170 |
| | Barstow | 3330 | 0.03 | 100 |
| | Lone Pine | 1375 | 0.08 | 110 |
| | Ridgecrest | 4000 | 0.02 | 80 |

necessary calculations, but few measurements were actually made of fallout radionuclides in air, soil, water, or foods during the early weapons test series to enable scientists to validate the results of their calculations.

Calculations of radiation doses to people from ingested fallout, as developed by the Off-Site Radiation Exposure Review Project involve four multiplying factors;

1. Site Specific Exposure Rate in Air at H + 12 Hours — mR/hr
   x
2. Fallout Deposition Calculation — $[\mu Ci/m^2]/[mR/hr]$
   x
3. Food Pathway Modeling — $\mu Ci$ Ingested$/[\mu Ci/m^2]$
   x
4. Tissue Dose per Unit Intake — rad/$\mu Ci$ Ingested

Table IV-4

Comparison of Estimated Radiation Exposures to Utah Residents from Nuclear Weapons Fallout Reported by Beck and Krey (1982) and Anspaugh and Church (1983)

| | Estimated Exposure - R | |
|---|---|---|
| Utah Location | Beck and Krey | Anspaugh and Church |
| Cedar City | 0.42 | 0.64 |
| Hurricane | 2.9 | 3.5 |
| La Verkin | 2.9 | 3.7 |
| Panguitch | 0.28 | 0.70 |
| St. George | 2.6 | 3.7 |
| Santa Clara | 1.7 | 4.3 |
| Veyo | 4.1 | 2.8 |
| Washington | 1.7 | 3.3 |

The exposure rates in air are specific to location and individual weapons tests and are taken from field measurements when available; otherwise fallout dispersion model calculations are used. The fallout deposition calculation is based upon relationships developed by Hicks (1981, 1981a and 1982). These provide a means for estimating the concentrations of single radionuclides deposited on ground surfaces based upon exposure rates measured in air at one meter above the surface. The food pathway model calculation is complex and requires much input information. This includes the name of the event, location of the exposed population, individual ages and dietary habits, seasonal agricultural factors, and environmental transport information. A diagram of this model is shown in Figure IV-18. The last factor in the ingestion pathway dosimetry calculation, tissue dose per unit intake of radionuclide, is obtained from other publications for different radionuclides (Eckerman et al. 1981, Killough et al. 1978, Dunning and Schwartz 1981, Hoenes and Soldat 1977, Mays and Lloyd 1966, Papworth and Vennart 1973).

In general, the most significant radiation doses to people that were calculated using the ingestion pathway model were those to the thyroid, lower large intestine, and bone marrow. These were mainly contributed by $^{131}I$, $^{133}I$, and $^{132}Te$ for the thyroid, $^{239}Np$, $^{89}Sr$, $^{93}Y$, $^{97}Zr$, $^{140}Ba$, and $^{147}Nd$ for the lower large intestine, and $^{89}Sr$, $^{90}Sr$, $^{131}I$, $^{132}Te$, $^{137}Cs$, and $^{140}Ba$ for the bone marrow. Ongoing work regarding the ingestion pathway model is focused on validating the calculations using measured relationships between radionuclide concentrations on pastures and in milk, grain, and beef (U. S. Department of Energy 1983a). Attempts are also being made to estimate the magnitudes of uncertainties in the calculated doses to individuals. Preliminary work suggests that the doses to individuals in a population could be represented by a lognormal distribution having a geometric standard deviation of approximately 2.7.

For inhaled fallout radionuclides, the Off-Site Radiation Exposure Review Project has estimated exposures to people based upon measured air concentrations of total radioactivity. If air concentration measurements were not made at a particular site, then measurements made at the nearest geographic site were used after being scaled by the relative radiation exposure intensities measured by ionization chambers one meter above the ground at each location. The dose calculation involves multiplication of five factors:

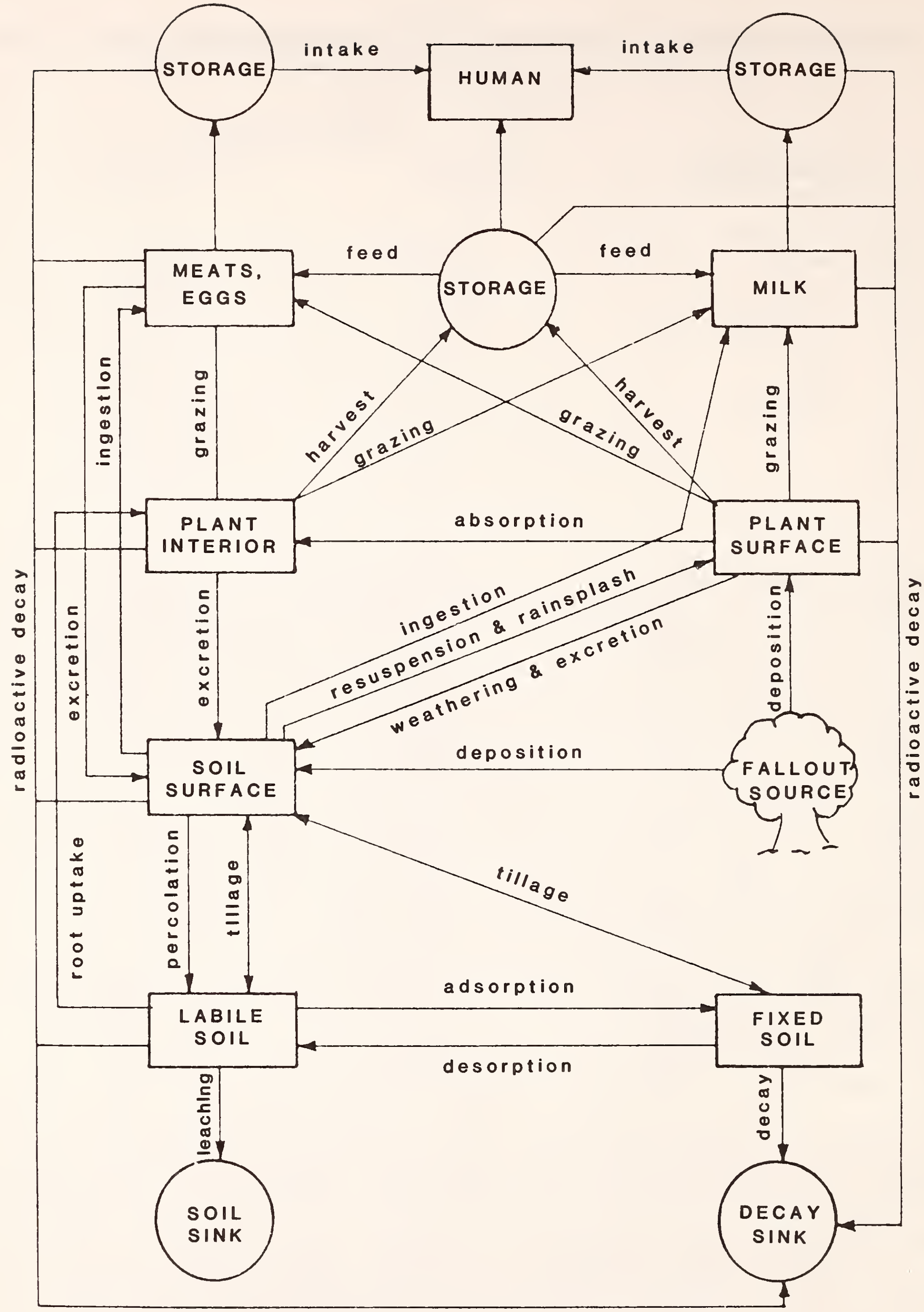


Figure IV-18. Schematic diagram showing the ingestion pathway model used by the Off-Site Radiation Exposure Review Project to calculate radiation doses to people living downwind from the Nevada Test Site during atmospheric nuclear weapons testing (U.S. Department of Energy 1980-1983).

| | | |
|---|---|---|
| 1. | Total Radioactivity Concentration in Air | $\mu Ci/m^3$ |
| | | x |
| 2. | Sampling Time | hr |
| | | x |
| 3. | Breathing Rate | $m^3/hr$ |
| | | x |
| 4. | Radionuclide Fraction of the Total Radioactivity | $\mu Ci/\mu Ci_T$ |
| | | x |
| 5. | Tissue Dose per Unit Intake | $rad/\mu Ci$ |

The total radioactivity measured in air is apportioned for single radionuclides based upon source term calculations reported by Hicks (1981). Tissue doses per unit intake of radionuclide were taken from the reports listed above related to the ingestion pathway model.

The most important inhaled radionuclides were estimated to be $^{239}Np$, $^{91}Sr$, $^{97}Zr$, and $^{93}Y$ for irradiation of the lower large intestine and $^{133}I$, $^{132}Te$, $^{135}I$, and $^{131}I$ for irradiation of the thyroid. Estimated dose to the thyroid from inhaled fallout was only about 6% of the dose resulting from ingestion. For most other organs, including the lung, the doses from inhaled radionuclides were about 30% of the doses from ingested radionuclides. Uncertainty associated with calculated tissue doses for inhaled fallout radionuclides was assumed to be the same as the uncertainty associated with calculations of doses from ingested radionuclides (i.e. geometric standard deviation 2.7). The possible magnitude of variability in human tissue concentrations of fallout radionuclides and trace metals taken up from the environment by inhalation and ingestion has been estimated by Cuddihy et al. (1979). They represented measured tissue concentrations in human populations by lognormal distributions and calculated geometric standard deviations of about 3 for the inhalation pathway and 2 for the ingestion pathway.

Because some parameters of the models used to calculate radiation doses from nuclear weapons test fallout vary with a person's age, the location of their residence and many lifestyle factors, doses must be calculated for single individuals or well-characterized populations based upon detailed personal information. This has been obtained from questionnaires distributed to people who lived in Nevada, Utah, and Arizona during the atmospheric test series. The results were used to calculate doses to individuals involved with law suits against the Federal Government and to other populations. Sample calculations are shown in Table IV-5 for residents of Lincoln County, Nevada as well as Washington and Iron counties in Utah. These counties are directly east of the Nevada Test Site and within 250 miles. The exposures resulted from three atmosphere tests, Annie (3-17-53), Harry (5-19-53) and Smoky (8-32-57), which caused more than 90% of the total estimated radiation doses to residents of Lincoln, Washington, and Iron counties. Shot Harry alone contributed about 70% of the total dose. Lifetime residents of Washington County received 2 to 4 times more radiation than the average doses shown in Table IV-5, whereas residents of Lincoln and Iron counties received about one-half of the listed doses. Doses to the total body, bone marrow, liver, lung, and kidney were estimated to be more than 90% due to external penetrating radiations. Seventy-six percent of the doses to the lower large intestine and 97% of the doses to the thyroid were estimated to be caused by ingested and inhaled fallout radionuclides.

Radiation doses to litigants in the trial of Irene Allen et al. vs. the United States of America calculated by the Off-Site Radiation Exposure Review Project are summarized in Table IV-6. They include whole body doses and doses to organs affected by cancers. Uncertainties associated with these values were expressed as geometric standard deviations that ranged between 1.4 for exposures that were mainly caused by external radiation to 2.7 for exposures that were mainly caused by internally deposited radionuclides. With the exceptions of radiation doses to skin and thyroid, all other doses to relevant organs were probably less than 5 rad.

Table IV-5
Average Radiation Doses to Residents of Lincoln, Washington, and Iron Counties
From Nuclear Weapons Tests Annie, Harry, and Smoky
(U. S. Department of Energy, 1982 through 1983)

| Organ | External Radiation (rad) | Internal Radionuclides (rad) | Total (rad) |
|---|---|---|---|
| Skin | 26<br>(100)[a] | -- | 26 |
| Total Body | 1<br>(92) | 0.08<br>(8) | 1.08 |
| Red Marrow | 0.9<br>(91) | 0.09<br>(9) | 0.99 |
| Liver | 0.86<br>(93) | 0.06<br>(7) | 0.92 |
| Lungs | 0.90<br>(97) | 0.03<br>(3) | 0.93 |
| Kidneys | 0.90<br>(94) | 0.06<br>(6) | 0.96 |
| Lower Large Intestine Wall | 0.81<br>(24) | 2.6<br>(76) | 3.38 |
| Thyroid | 1.1<br>(3) | 36.5<br>(97) | 37.6 |

[a]Numbers in parentheses are the percentages of the total doses contributed by external radiation and internally deposited radionuclides.

Epidemiologic Studies of Fallout-Exposed Populations

Epidemiologic studies of people exposed to fallout in Utah, Nevada, and Arizona have mainly focused on leukemia and thyroid cancer. Leukemia is the first type of cancer that was found in excess in the Japanese atomic bomb survivors (National Research Council 1980). The excess incidence became apparent 3 to 4 years after exposure, but only in survivors that received more than 100 rad. It began to decline after 15 years, but it was still apparent even after 25 years. Because the doses to bone marrow of people living near the Nevada Test Site were estimated to be less than 5 rad, an increase in leukemia incidence is not likely to be detected. Increased incidence of thyroid cancer in people living near the Nevada Test Site was also thought to be possible because excess thyroid cancers and nodules had been observed in Marshall Island natives who were exposed to high levels of fallout from nuclear weapons tests conducted in the Pacific.

Table IV-6

Radiation Doses to Litigants in the Trial of Irene Allen *et al*. vs. The United States of America Estimated by the Off-Site Radiation Exposure Review Project

| Principle Residence | Litigant | Wholebody Dose | Relevant Organ |
|---|---|---|---|
| Veyo, Utah | | | |
| | Willard Bowler | 4.5 | Skin (310 rad) |
| St. George, Utah | | | |
| | Arthur Bruhn | 1.8 | Bone Marrow |
| | Karlene Hafen | 2.2 | Bone Marrow |
| | Lisa Pectol | 0.5 | Brain |
| | Jacquelynn Sanders | 2.6 | Thyroid (41 rad) |
| | William Swapp | 3.9 | Kidney |
| | Irma Wilson | 2.7 | Bladder |
| Washington, Utah | | | |
| | Sheldon Nisson | 2.7 | Bone Marrow |
| Fredonia, Arizona | | | |
| | Lenn McKinney | 1.7 | Bone Marrow |
| | LaVier Tait | 2.1 | Bone Marrow |
| Hiko, Nevada | | | |
| | Kent Whipple | 0.7 | Thorax |
| Pinoche, Nevada | | | |
| | Delsa Bradshaw | 0.5 | Lung |
| | Lionell Walker | 0.7 | Prostate |
| Cedar City, Utah | | | |
| | Donna Berry | 0.3 | Ovaries |
| | Jeffrey Bradshaw | 0.5 | Lymphatic S. |
| | John Crabtree | 0.4 | Bone Marrow |
| | Glen Hunt | 0.5 | Pancreas |
| | Sybil Johnson | 0.4 | Bone Marrow |
| | Daisey Prince | 0.4 | Lymphatic S. |
| | Norma Pollitt | 0.3 | Breast |
| | Geraldine Thompson | 0.3 | Ovaries |
| | Catherine Wood | 0.4 | Colon |
| Parawan, Utah | | | |
| | Melvin Orton | 0.5 | Stomach |
| | Peggy Orton | 0.5 | Bone Marrow |

Their estimated thyroid doses are 220 to 450 rad and the latent period has varied between 11 and 22 years. As shown in Tables IV-5 and IV-6, radiation doses to the thyroids of people living directly downwind from the Nevada Test Site were approximately 40 rad.

At least three important difficulties have arisen in epidemiologic studies of people exposed to nuclear weapons fallout near the Nevada Test Site. First, because most of these areas are sparsely populated, the numbers of residents are inadequate for studying the effects of low levels of radiation. Second, a high percentage of the people are Mormons who have very different spontaneous cancer risks compared to potential control populations living in other areas of the United States. Third, the availability of medical services in southern Utah changed markedly between 1940 and 1980 so that the consistency of diagnosis and reporting of diseases over the critical time periods is questionable (Enstrom 1980).

Two of these difficulties are illustrated in Table IV-7 which lists cancer rates in Utah for the 11-year period, 1967 through 1977. The northern Utah counties shown here have larger populations and more uniform cancer incidence rates compared to the southwestern counties. The total cancer incidence rate in Utah is only about 80% of the average for the United States. A large part of this difference is due to a lower lung cancer incidence in Utah, presumably because of a lower percentage of cigarette smokers among Mormons. However, for a few other cancer types, such as melanoma, the incidence rates in Utah are higher than the average incidence rates for the

Table IV-7

Relevant Cancer Incidence Rates for the More Populous Northern Utah Counties Compared to Those in Southwest Corner of Utah Nearest to the Nevada Test Site. Date Were Taken From the Utah Cancer Registry 1967 to 1977.[a]

| County | Approximate Population | Acute Leukemia | Thyroid | Melanoma of Skin | Lung | All Sites |
|---|---|---|---|---|---|---|
| Northern | | | | | | |
| Salt Lake | 400,000 | 4.7 (224) | 4.1 (191) | 7.5 (338) | 25.7 (1029) | 304 (12649) |
| Weber | 110,000 | 4.6 (60) | 4.7 (61) | 7.3 (90) | 21.9 (253) | 299 (3515) |
| Utah | 100,000 | 4.0 (51) | 6.4 (76) | 7.2 (80) | 21.5 (206) | 286 (2890) |
| Davis | 60,000 | 4.2 (34) | 4.6 (42) | 7.8 (67) | 20.9 (105) | 290 (1685) |
| Cache | 40,000 | 3.3 (16) | 5.0 (20) | 6.3 (26) | 12.8 (49) | 254 (992) |
| Southwestern | | | | | | |
| Washington | 14,000 | 2.7 (4) | 2.1 (3) | 4.4 (7) | 16.6 (27) | 255 (400) |
| Iron | 11,000 | 4.7 (6) | 1.8 (2) | 3.4 (4) | 19.9 (21) | 270 (288) |
| Beaver | 4,000 | 6.5 (3) | 5.6 (2) | 2.0 (1) | 21.0 (10) | 267 (123) |
| Kane | 2,500 | 3.5 (1) | 2.8 (1) | 17.4 (4) | 18.2 (5) | 268 (67) |
| Garfield | 3,000 | 5.8 (2) | 2.3 (1) | 2.6 (1) | 14.8 (5) | 248 (85) |
| State of Utah | 910,000 | 4.3 (463) | 4.5 (473) | 7.4 (741) | 23.2 (2091) | 293 (27266) |
| United States | | 4.3 | 4.2 | 4.9 | 36.5 | 350 |

[a]Data are annual age adjusted rates per 100,000. Numbers in parentheses are the total cases observed during the 11-year period.

United States. The Utah Cancer Registry data indicate that only 16 acute leukemias and 10 thyroid cancers occurred in the five southwestern counties of Utah during this 11-year period. Thus, few, if any, cancers could be ascribed to radiation exposures from nuclear weapons fallout during this period when its impact should have been greatest, but how this risk should be evaluated has been the subject of much controversy. Whether or not the expected cancer rates for southwestern Utah counties should be calculated from northern Utah populations, the United States population, or by some other means depends upon the type of cancer being evaluated as can be seen in Table IV-7. But in any event, there will always be a large uncertainty when comparing the observed and calculated expected cancer incidence rates for southwestern Utah to determine the possible impact of radiation because the numbers of observed cases are small and the calculated cancer rates for these counties are highly variable.

The most widely publicized and controversial epidemiologic study of cancer mortality related to nuclear weapons fallout in Utah was reported by Lyon et al. (1979, 1980). They focused on leukemia in children under 15 years of age although additional information on other childhood malignancies was also summarized. The population of Utah was divided into 12 northern counties and 17 southern counties. (The southern counties were also subdivided into 5 border counties and 12 interior counties, but this added complication has limited importance to the present discussion.) Lyon et al. used death certificates from the period 1944 to 1975 to tabulate all deaths due to childhood cancers and blood disorders. Individuals who died before 1951 and were less than 15 years of age were put into the early low exposure group. Children who were alive between 1951 and 1959 but died at less than 15 years old were put into the high exposure group. Children born after 1959 who died before 1975 were put into the late low exposure group. This cohort grouping is illustrated in Figure IV-19.

In southern Utah counties, Lyon et al. reported 32 leukemia deaths in the high exposure cohort, whereas they expected only 13.1 based upon age adjusted incidence rates taken from the low exposure cohort. In northern Utah counties, 152 leukemia deaths were observed whereas only 119 were expected. Thus, the increased leukemia risk appeared to be stronger in the southern counties compared to that in the northern counties. Lyon et al. suggested that this resulted from their closer proximity to the Nevada Test Site and presumably higher radiation exposures than experienced by people living in the northern Utah counties. This assumption seems inappropriate today because the studies of Beck and Krey (1982) described above indicate that people who lived in northern and southern Utah counties experienced similar radiation exposures from nuclear weapons fallout.

The studies of Lyon et al. were reviewed by Land (1979), Enstrom (1980), and Land et al. (1984). Land et al. (1984) repeated the analysis of Lyon et al. using data from the National Center for Health Statistics. These data covered the time period 1950 through 1978, whereas Lyon et al. used data from 1944 through 1975. Land et al. confirmed that the high exposure cohorts of Lyon et al. did show higher childhood leukemia mortality than the low exposure cohorts, but that this result was equal for northern and southern Utah. They also showed that the same pattern of leukemia mortality occurred in eastern Oregon, Iowa, and the United States as a whole. Thus, results of the analysis by Lyon et al. are not unique with respect to distance or direction from the Nevada Test Site. Land et al. also suggested that a marked under-reporting of leukemia in southern Utah was likely prior to 1950. This could have been due to the limited availability of medical care in that area as described by Enstrom (1980).

The reviews of Land et al. (1984) and Enstrom (1980) also emphasized that the analysis of Lyon et al. (1979) showed mortality from other childhood malignancies in southern Utah decreased at the same time that leukemia mortality supposedly increased. This pattern is not consistent with the hypothesis that radiation caused the calculated increase in leukemia in southern Utah

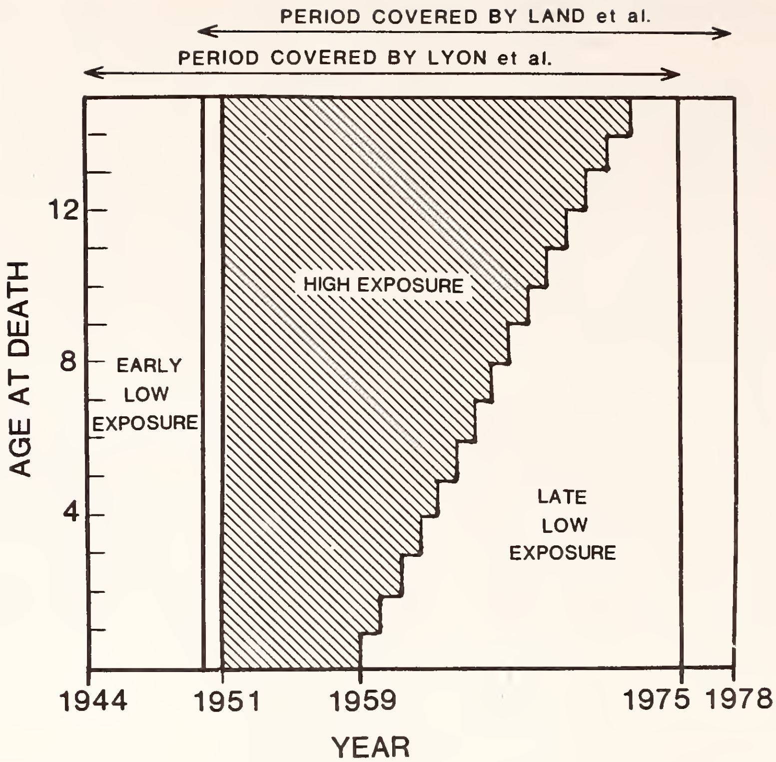


Figure IV-19. Illustration of high and low exposure cohorts of children under 15 years of age who lived in Utah during atmospheric nuclear weapons testing at the Nevada Test Site used by Lyon *et al.* (1975), and Land *et al.* (1984) to evaluate leukemia risks from exposures to radioactive fallout.

because the incidences of other types of cancers should also have increased. Thus, Land et al. suggested that the result of the cohort analysis by Lyon et al. was likely due to the confounding factor of progressive increasing survival of young leukemia patients during the period 1950 through 1978 related to improved cancer treatment programs.

Other epidemiologic studies of people living near the Nevada Test Site have focused on the incidence of thyroid disease, especially in school age children (Rallison et al. 1974, 1975; Weiss et al. 1967, 1971). The thyroids of southern Utah and Nevada residents probably received about 40 rad of radiation. This was mainly due to ingesting radioiodine in milk and the bulk of this exposure occurred during the Upshot-Knothole series in 1953. Because the latent period for developing thyroid cancer from exposure to radiation is 11 to 22 years, the most appropriate period of studying thyroid disease in southern Utah and Nevada residents is 1964 through 1975.

The first study of Weiss et al. (1967) included 1,162 thyroid surgery cases in Utah between 1948 and 1962. The rate of surgeries was relatively constant over the 15-year study period and it was about five times higher in females compared to males. However, there was some suggestion in the data that thyroid cancer incidence may have increased during the last 5-year period of the study -- 1958 through 1962. Because no attempt was made to document the exposures of these patients to fallout, nor were adequate numbers of exposed and control cases identified for comparison, further studies were recommended.

Later reports by Weiss et al. (1971) and Rallison et al. (1974, 1975) describe a continuing study that included 5,179 school children living in Nevada, Utah, and Arizona. The children were between 11 and 18 years of age when given medical examinations during the period 1965 through

1971. Detailed histories of residence were obtained to determine their previous likelihood of exposure to weapons test fallout. The rates of occurrence of thyroid nodules in these children were 13/1000 in the known exposed group, 14/1000 in nonexposed residents of Utah and Nevada, and 9/1000 in nonexposed residents of Arizona. Two children were found to have carcinoma of the thyroid, but they were in the nonexposed groups. Thus, no evidence of increased incidence of thyroid disease in southern Utah and Nevada has been developed to date.

Another survey of cancer incidence in people living in the southwest corner of Utah and the neighboring area of Nevada was conducted by Johnson (1984) just prior to the courtroom trial in the litigation of Allen et al. vs. the United States of America described below. The survey included 4,125 people who were identified from area telephone directories published in both 1951 and 1962. Families of these people were contacted by volunteer interviewers to obtain information about the occurrence of cancer in their families. Additional information was requested about any acute ill effects that people experienced due to their previous exposures to fallout. By comparing the information obtained from this survey with information on cancer rates in other Utah residents (Lyon et al. 1980a), Johnson concluded that people who lived in the high fallout area had excess incidences of stomach, colon, breast, thyroid, brain and bone cancers, and melanoma. Criticisms of the Johnson report have focused on: (1) there was no medical verification of any health effects reported to the interviewers, (2) there was no verification as to when the deaths or diagnoses of cancer occurred, (3) there were inadequate checks against multiple reporting of cancers, and (4) the questionnaire was not prepared or administered in an acceptable manner so as to avoid biased reporting of information.

Few studies have attempted to identify health effects from radiation exposures to on-site participants in the nuclear weapons test program. This is probably due to the low levels of radiation received by military and nonmilitary personnel, and the generally held belief of scientists that health effects are not likely to be detected by such studies. A preliminary report was published by Caldwell et al. (1980) on leukemia cases among military participants at the test, Smoky, conducted in 1957. The initial interest in military participants at Smoky began in 1976 when a leukemia patient inquired about the possibility that his disease was caused by radiation exposure at the Nevada Test Site.

To date, 3,224 men have been identified from military records as being present at the Smoky test. Ten cases of leukemia have occurred in this group, whereas the calculated expected incidence was reported to be 3.5. The average radiation exposure recorded for 8 of the 10 leukemia cases is 1.2 rem. The report describing this study is preliminary because further attempts are being made to identify and study more of the participants in nuclear weapons tests. Certainly much stronger evidence would be needed to convince radiation scientists that such low radiation exposures could cause a measurable increase in leukemia in light of abundant evidence to the contrary from many other epidemiologic studies. It is generally thought that the 10 cases of leukemia observed among Smoky participants is a chance occurrence or cluster. No evidence has been found that leukemia mortality was increased among participants at the Plumbbob tests other than Smokey or among participants at Upshot-Knothole, Greenhouse, Castle, or Redwing (Robinette et al. 1985). Many such leukemia clusters have been investigated by the Center for Disease Control because such clusters were used to support the theory that leukemia could be caused by a communicable virus.

Litigation Related to Nuclear Weapons Testing in Nevada

A. Allen et al. vs. The United States of America

In 1979 a major civil action styled Irene Allen, et al. vs. United States was filed in the United States District Court for the District of Utah. Nearly 1,200 plaintiffs in that suit seek compensation for personal injuries to themselves or death to family members. Claims alleged

that internal organ cancers, skin cancers, and leukemias were caused by exposure to radioactive fallout from atmospheric nuclear weapons tests at the Nevada Test Site. Twenty-four randomly selected claims were tried to the Court in the Fall of 1982. By the conclusion of the three-month trial, nearly 7,000 pages of testimony had been recorded, and 1,692 documentary exhibits were submitted. United States District Judge Bruce S. Jenkins deliberated for 17 months before returning his decision on May 9, 1984. In the decision, awards were granted to eight people who developed leukemia, one person who developed breast cancer, and one person who developed thyroid cancer. No awards were granted to 14 other plaintiffs.

Because the total amount of evidence presented is so large, only a summary of a few major points is presented here. These are generally divided into arguments concerning (1) the jurisdiction of the court, (2) alleged negligence on the part of the Government or its agent in conducting the weapons tests, and (3) evidence that radiation from weapons fallout caused cancers in the plaintiffs.

1. Jurisdiction of the Court

From the outset of the Allen litigation, one of the primary legal defenses the Government asserted was its immunity under the discretionary function exception to the Federal Tort Claims Act. This defense was briefed and argued along with other motions early in the case and again immediately prior to trial. The Court denied the motions each time but allowed the Government to renew them as the record became more fully developed.

The Government argued -- and the Court agreed -- that the original decision to test on the continent, the selection of Nevada Proving Grounds as the place to test, and the decisions to conduct each series of tests were discretionary and outside the Federal Tort Claims Act limited waiver of sovereign immunity. The Government argued - and the Court disagreed -- that the Government's actions in implementing some offsite safety aspects of the discretionary decisions were likewise immune.

The basis of the Government's argument lies in a 30-year old Supreme Court case called Dalehite vs. the United States of America. The majority there stated that immunity goes to more than the discretion which results in the initiation of programs and activities. It must, of necessity, go to the acts carried out in implementing the decision. However, the Courts have not defined precisely where discretion ends. At the time Judge Jenkins ruled, this decision had never been reversed. Nonetheless, lower courts had wrestled with the principle in a way that most commentators felt had eroded Dalehite's apparently broad application. Since the Allen decision, the Supreme Court in the Varig Airlines case has reaffirmed the principles enunciated in Dalehite. Subsequently, the United States Court of Appeals for the Third Circuit dismissed the Three Mile Island case on the discretionary function exception, and Judge Koppel dismissed the uranium miners litigation in Arizona on the same basis.

The Government's motion to dismiss 19 of the 24 cases because the claims were barred by the statute of limitations was denied. The Court determined that the statute commences to run from the point at which the plaintiff's knowledge of his injury and its cause is sufficient to justify fairly placing the burden on inquiry on him. The standard is derived from cases involving diseases with long latency periods where it is impossible to know of the injury for many years. The Court also noted that the Government probably contributed to the plaintiffs lack of knowledge concerning the cause of their injuries by its "reassurances," over the period of atmospheric testing, that there was no danger.

2. Alleged Negligence by the United States Government

The plaintiffs alleged that the Government was negligent because (1) the off-site radiation safety program was inadequate, and (2) they failed to warn the public of the dangers of radioactive fallout. Mr. Butrico, an off-site radiation monitor who was at St. George when test

Harry was detonated on May 19, 1953, testified for the plaintiffs. He related how the fallout trajectory changed due to an unexpected wind shift and headed directly toward St. George. This prompted actions to minimize the exposures to the fallout, but Mr. Butrico considered the actions to reduce exposures to nearby populations to be too little and too late because of inadequate preparations.

Dr. Harold Knapp, an employee of the Atomic Energy Commission who was not directly involved with the nuclear weapons testing program, also testified concerning alleged negligence. He believed that his analysis of radiation doses to human thyroids from radioiodine in fallout was suppressed by the Atomic Energy Commission because it indicated that there may have been very high exposures to people living in Utah and Nevada. However, this report was published within one year of the initial draft after peer review (Knapp 1964).

Dr. Karl Morgan testified that the radiation safety program at the Nevada Test Site during the atmospheric testing program was inadequate by comparison to the health physics program he established at Oak Ridge. He acknowledged that in many respects procedures used at the Nevada Test Site did conform with the state of knowledge that existed during the testing period, but that he disagreed with the prevailing authority of the Atomic Energy Commission.

James Reeves, former Test Manager, and Oliver Placak, former Director of Off-Site Safety for the Public Health Service, testified for the United States Government. They described the off-site radiation safety and public information programs and how they were increased throughout the testing program. Dr. Gordon Dunning, a representative of the Atomic Energy Commission Division of Biology and Medicine, testified as to how radiation exposure guidelines were developed and adhered to.

In their Proposed Findings of Fact, attorneys for the United States Government also argued that in common law the legal duty to warn or to take care requires that the danger must be able to be perceived. Thus, the Government should not be held responsible on the theory of negligence for an injury from an act or omission unless the act or omission involved a perceived danger to another. The Government's position is that (a) serious risks to human health were not perceived during the atmospheric test series, and (b) the alleged risks have not been demonstrated by the plaintiffs.

The court decided that the Government was bound by the highest degree of care in conducting all aspects of nuclear weapons testing in light of the best available scientific knowledge. This is due to (a) the relatively high degree of risk of serious injury to the public, (b) the increased hazard to children, and (c) the knowledge of test site scientists and radiation experts in contrast to the lack of public knowledge on radiation hazards. The court decided that the plaintiffs did not establish that test site personnel negligently failed to exercise care in determining how to detonate each nuclear device under existing meterological conditions. However, it was decided that monitoring activities in areas surrounding the Nevada Test Site were persistently negligent in philosophy and action, and that the monitoring produced inadequate data for determining external and internal radiation exposures resulting in the present inabilities to make reasonably confident estimates of individual doses and risks. It was also thought that Nevada Test Site personnel should have warned nearby residents of the dangers of radiation, of the times of scheduled tests, and of simple measures that were used on-site and could be used off-site to reduce radiation exposures (e.g., remaining in shelters while fallout clouds were passing, washing clothes, and bathing).

3. Health Effects Causation Testimony

Government attorneys argued that in order to establish a case of wrongful injury, plaintiffs must show that radioactive fallout was more likely the cause of the cancers than other possible causes or that the cancers would not have developed were it not for the exposures to

fallout (Gill et al. 1982). They also argued that it is not sufficient to prove that the Government's actions were only one of two or more possible causes of the cancers. To argue for causation, the plaintiffs used four epidemiologic studies on populations that lived near the Nevada Test Site.

The first was a study of leukemia clusters conducted by the Center for Disease Control and described by Dr. Clark Heath. These unpublished studies were originally conducted to learn more about the possible viral etiology of leukemia. Clusters were identified in southern Utah, Nevada, and Arizona, but they did not appear more frequently than in other areas of the United States and no reason for the clusters was established by the Center for Disease Control. The clusters did not appear to be related to nuclear weapons fallout because they occurred about as frequently during the 1950s as during the 1960s, and there was no uniform increase in leukemia incidence in response to the rather uniform radiation exposures that occurred near the Nevada Test Site.

The second study described in Section III was by Lyon et al. (1979, 1980) which reported an association between fallout and childhood leukemia. Rebuttal testimony was presented to indicate that (a) it involved few cases of leukemia that implied a low statistical significance, (b) it was based on an incorrect assumption that people who lived in southern Utah received higher radiation exposures than those who lived in northern Utah, and (c) the same pattern of increased leukemia incidence as reported in Lyon's high and low exposure groups also occurred in eastern Oregon, Iowa, and in the total United States population.

The third study was described by Dr. Caldwell (1980) and involved a calculated excess of leukemia in military personnel who participated in the weapons test, Smoky. He emphasized the small number of leukemia cases that were involved (10 observed when 3.5 were expected), and that the study did not reach any conclusion with respect to the causes of these leukemia cases.

The fourth study, also discussed above, was reported by Johnson (1982). Data used in this study were standardized cancer rate ratios (observed cases/expected cases). Johnson concluded that cancers of the stomach, breast, thyroid, bone, brain, melanoma, and leukemia had occurred in excess in southern Utah. Overall, Johnson claimed to have observed 118 cancers between 1958 and 1966 and 170 between 1972 and 1980 when he expected only 72 and 102, respectively. However, as described above, the diagnoses of cancers and their times of occurrence were not checked against medical records, and the calculations of true or expected cancer incidence rates have not been verified. Nevertheless, Dr. Gofman used these data to calculate probabilities that the cancers developed by the plaintiffs in this litigation were caused by their exposures to nuclear weapons fallout (Gofman 1982).

Dr. Gofman testified that it was necessary to calculate radiation doses to individual plaintiffs in order to estimate their probabilities of developing radiation-induced cancers. Because he did not think that previous dosimetry measurements could be used for this purpose, he calculated these doses as outlined in Figure IV-20. First, Johnson's ratios of observed/expected cancers (expressed as a percentage) were divided by Gofman's risk factors expressed as the expected percent increase in incidence per rad of exposure. This resulted in estimates of the average doses to members of the exposed populations. In the second step, these doses were multiplied by the fractions of time between 1951 and 1961 that individual plaintiffs lived in southwestern Utah. This provided estimates of radiation doses to individuals. In the last step, Gofman multiplied the calculated individual doses by risk factors that he developed previously (Gofman 1981, Tables 56A, 568 and 61). This produced his estimates of the percent increases in cancer risk for individual plaintiffs. Separate calculations were performed for thyroid cancer, bone cancer, leukemia, melanoma, and all other cancers.

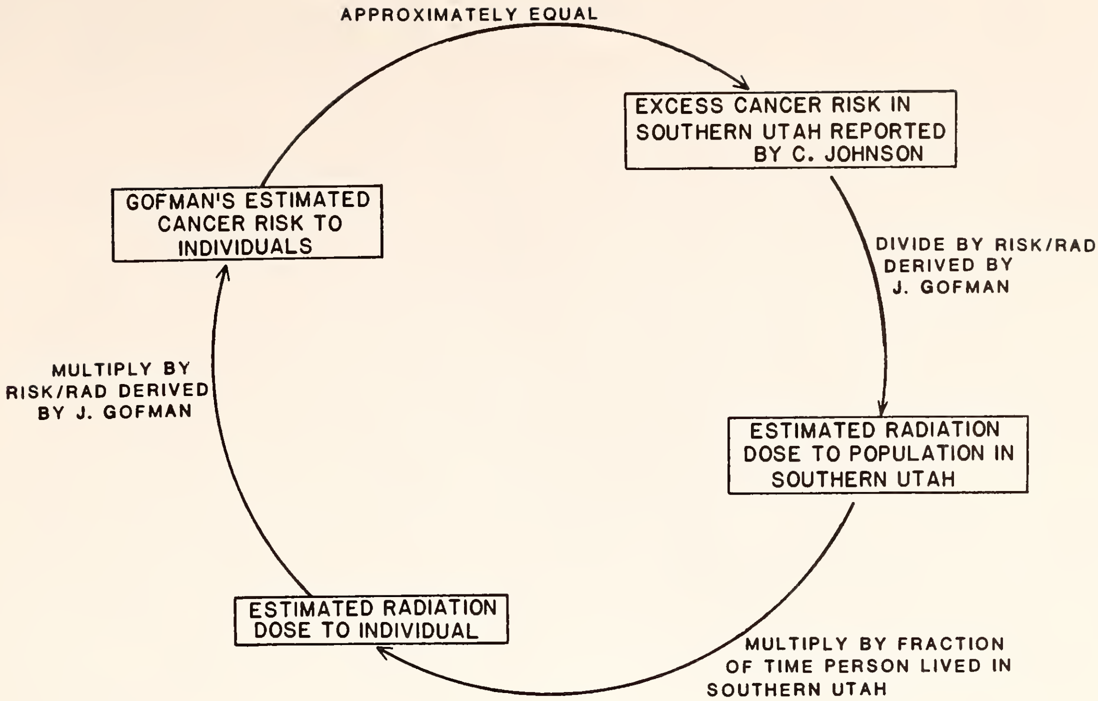


Figure IV-20. Illustration of technique used by Gofman to estimate cancer risks for litigants in Allen *et al.* vs. the United States of America. Risks to Utah residents were based solely on a cancer survey conducted by Johnson.

Government attorneys showed that Gofman's estimates of the increased cancer risk for individual plaintiffs were approximately equal to the increased population cancer risks calculated by Johnson. The individual risks were simply adjusted downward in proportion to the fractions of time that individual plaintiffs lived in southwestern Utah during the atmospheric test series. Although Gofman's causation testimony was complex, it depended totally on the unverified cancer survey described by Johnson.

The percent of the total cancer risk that was caused by a plaintiff's exposure was calculated by Gofman using the expression;

$$\text{Percent Radiation Causation} = \frac{\text{Radiation Risk}}{\text{Spontaneous Risk} + \text{Radiation Risk}} \times 100$$

The radiation risk was equal to the dose in rad multiplied by the percent increase in risk per rad. The spontaneous risk was 100%. Using leukemia for example, Gofman assumed that the spontaneous risk would be increased by 16.96% per rad of exposure and that the relevant dose was 20.2 rad for a plaintiff who lived in southern Utah from 1951 to 1961. Thus, the risk attributable to radiation was estimated to be

$$\frac{16.96 \times 20.2}{100 + 16.96 \times 20.2} \times 100 = 74\%$$

As an average, radiation doses to the plaintiffs as calculated by Gofman were about 40 times larger than those calculated by the Off-Site Radiation Exposure Review Project. The probabilities that these exposures caused cancers in the plaintiffs were estimated by Gofman to be greater than 50% for six of the seven leukemia cases, but only for three of the remaining 17 cancers. The latter three cases were cancers of the thyroid, brain, and Hodgkins disease. For all cases, Gofman thought that radiation was a contributing cause of cancer, but he did not indicate that it was the most likely cause in any case. The testimony of Gofman and Johnson was all of the testimony presented by plaintiffs' attorneys on the subject of causation.

Attorneys for the Government presented testimony on causation by 10 cancer specialists from medical centers throughout the United States. In each case, testimony was given that the radiation exposures from fallout were not large enough to be the primary cause of the plaintiffs' cancers. This testimony was coupled to specific studies of health effects in people exposed to different types of radiation and to the experts' experiences in clinical medicine.

The court concluded that the lack of adequate radiation monitoring and public warnings was strong reason to shift the burden of proof in cause-in-fact questions over to the Government and that the Government was negligently engaged in conduct that created risks consistent with the types of harm suffered by the plaintiffs. Therefore, when persuasive proof to the contrary was absent, the court decided it could reasonably conclude that radiation caused the condition if (a) the plaintiff developed a cancer that occurred in excess in the exposed population, (b) the type of injury was known to be caused by radiation, (c) the person lived near the Nevada Test Site between 1951 and 1962, and (d) other factors such as latency were consistent.

For three plaintiffs who developed an adenocarcinoma of the prostate, a sarcoma of the kidneys and a brain tumor, the court decided that these injuries were not known to be caused by ionizing radiation. For two plaintiffs who developed cancers of the ovaries, two who developed lung cancers, and one each who developed a malignant melanoma, carcinoma of the colon, carcinoma of the bladder, Hodgkin's disease and cancer of the stomach, the court decided that no excess incidences were observed in the exposed population. For one plaintiff who developed a histiocytic lymphoma, the court decided that neither the association with radiation or its occurrence in the exposed population were strong enough to conclude radiation causation. For eight plaintiffs who developed leukemia, one who developed breast cancer and one who developed thyroid cancer, the court granted awards because of their strong associations with radiation in general.

B. Roberts et al. and Nunamaker et al. vs. the United States of America

Plaintiffs, Roberts et al. and Nunamaker et al. brought suit against the United States of America in 1982 for radiation exposures to Harley Roberts and William Nunamaker that were alleged to have caused their leukemias. Roberts and Nunamaker had worked at the Nevada Test Site and were exposed to radiation from nuclear weapons fallout released during the Banbury test.

Banbury was a 20 kiloton device detonated 900 ft below ground near the northern border of Yucca Flat on December 18, 1970 (Kerr 1978). Radioactivity began venting 3.5 minutes after detonation and continued for about 24 hr. Airborne radioactivity drifted across the Test Site passing off-site to the north and east. Eighty-six on-site workers were decontaminated and the highest recorded exposures were about 1 rem whole-body and 3.7 rem to the thyroid. The highest off-site radiation exposures were estimated to be 0.04 rem total body and 0.5 rem to the thyroid.

During the litigation, it was established that the relevant doses to bone marrow were 0.42 rem for Roberts and 0.08 rem for Nunamaker. Testimony was presented on radiation-induced cancer similar to that described above. After the trial concluded, the decision of the court stated that epidemiologic studies presented by the plaintiffs were not, by themselves, a sufficient basis for concluding to a reasonable degree of medical certainty, that radiation received while working at the Nevada Test Site caused the leukemias. The claims against the

United States were thereby dismissed. This decision is important to other radiation injury litigations wherein the only causation testimony that may be presented relies solely upon statistical epidemiologic studies of large populations.

C. Bullock et al. vs. The United States of America

Plaintiffs in the litigation of Bullock et al. vs. the United States of America sought relief for the loss of sheep asserted to have been caused by radiation from nuclear weapons tests conducted during 1953. The sheep were pasturing in southern Nevada and Utah when large numbers of deaths were reported among ewes and their newborn lambs. About 4,000 sheep died ( 2000 ewes and 2,000 lambs) during the spring lambing period, beginning in early April and ending in mid May.

Among the early weapons tests in the Upshot-Knothole series of 1953 only Nancy produced a significant fallout pattern that extended north and east of the Nevada Test Site where the sheep were grazing (U. S. Department of Energy 1982). After hearing reports of the sheep deaths, the Atomic Energy Commission requested that a small group of veterinarians investigate the reported deaths to evaluate the most likely causes. They generally concluded that the deaths were caused by the weakened condition of the flocks due to poor pasture conditions and the stress of lambing. Other scientific experts at Hanford were asked to compare lesions observed in the Utah sheep with those observed in their laboratory studies of sheep that ingested large quantities of radioiodine (Bustad et al. 1953, 1957). Bustad concluded that the deaths of the Utah sheep could not have been due to fallout unless there was evidence that the radiation exposures were sufficiently large to render the sheep hypothyroid. This was not the case for a sampling of sheep whose tissues were examined shortly thereafter.

In spite of these reports, the ranchers filed a claim against the United States of America in 1956. Relying mainly on the expert testimony of the veterinarians who investigated the sheep deaths in 1953 at the request of the Atomic Energy Commission, Federal Judge A. S. Christensen dismissed the ranchers claims for compensation. This decision remained uncontested for about 25 years. However, the ranchers' interests were revived by testimony in a Congressional Hearing related to nuclear weapons testing in 1979 and by a report on radiation doses to the sheep by Harold Knapp (unpublished) 15 months later. The Knapp report suggested that the ewes might have received radiation doses between 1,500 and 6,000 rad to their gastrointestinal tracts and that fetal lambs may have received thyroid doses of 20,000 to 40,000 rad.

In February 1981, ranchers Bullock et al. filed a request in the District Court of Utah to have the initial judgment finding the United States blameless in the sheep deaths set aside. The same Federal Judge, A. S. Christensen, heard testimony regarding this request that asserted information was withheld from them in the initial suit because witnesses for the Government were pressured and that this constituted a fraud on the court. The court entered a judgment in this action setting aside the inital judgment of 1956 by reason of fraud. This judgment was subsequently appealed to the Tenth Circuit Court of Appeals which made a ruling on November 23, 1983, finding in favor of the United States. In summary,

> "We have considered this carefully (with other factors raised by the trial court) and must conclude that nothing was demonstrated which would constitute fraud on the court.
>
> We must thus conclude that the trial court was so in error and its conclusion and judgment constituted an abuse of discretion. The award of attorneys' fees must also be set aside." (U. S. Court of Appeals, Tenth Circuit, 1983).

In response to the renewed interest in the deaths of sheep in Utah, scientists from the Off-Site Radiation Exposure Review Project and the Battelle Pacific Northwest Laboratories also made estimates of the radiation exposures. These are summarized in Table IV-8. They indicate that Knapp probably overestimated these doses by a factor of 50 to 100 times. Although these

Table IV-8

Comparison of Calculated Radiation Doses in rad to Sheep Grazing North of the Nevada Test Site in Spring 1953

| Organ | Pennoyer Valley Knapp | Pennoyer Valley PNL | Pennoyer Valley ORERP | Cedar City ORERP |
|---|---|---|---|---|
| EWES | | | | |
| Total body | 40- 170 | 3 | 5 | -- |
| GI tract | 1,500- 6,000 | 4-200 | 6.4 | 5 |
| Thyroid | 10,000-40,000 | 400 | 110 | 280 |
| FETAL LAMBS | | | | |
| Total body | 17- 56 | < 6 | 5.1 | -- |
| Thyroid | 20,000-40,000 | 700 | 410 | 1100 |

calculated doses may have been as high as several hundred rad to the thyroid, it is important that Bustad did not find damage to sheep thyroids at these dose levels or over similar periods of time. These are critical points opposed to the conclusion that the sheep also suffered other radiation caused injuries.

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## SECTION V

## OCEANIC NUCLEAR WEAPONS TESTS

The Atomic Energy Act, signed by President Truman on August 1, 1946, transferred control of nuclear weapons from the military to the civilian Atomic Energy Commission effective January 1, 1947. However, the United States Navy was concerned about the effectiveness of nuclear weapons against ships and wanted to test an air burst and an underwater detonation on a surface fleet before the Atomic Energy Commission assumed control over the new weapon. Therefore, the United States Army Corps of Engineers, Manhattan District, established Joint Task Force One to coordinate various aspects of both military and civilian involvement. This first nuclear weapons test series was known as Operation Crossroads and detailed plans for the tests were developed and approved by President Truman on January 10, 1946.

An early task of Operation Crossroads was to identify a suitable site for the nuclear weapons tests. Planning specified that the test site be: (1) under the control of the United States, (2) uninhabited or subject to evacuation without imposing unnecessary hardships on large populations, (3) within 1,000 miles of a B-29 aircraft base--in anticipation that one bomb would be delivered by aircraft, and (4) free from storms and extreme cold with a protected anchorage at least 6 miles in diameter--large enough to accommodate the target fleet and additional support vessels. Additional requirements specified that the site should: (5) be a suitable distance from cities and population centers, (6) have predictable wind patterns from sea level to an altitude of 60,000 feet, and (7) have water currents not passing near inhabited shore lines, shipping lanes, or fishing areas. All of these requirements recognized the need to reduce or eliminate potential radioactive contamination of the support fleet and nearby inhabited areas. Several sites in the Caribbean, Atlantic, and Pacific were considered, but the central Pacific had the most appropriate small islands set in otherwise large areas of empty ocean with acceptable climates in the trade-wind zone.

The Marshall Islands in the eastern part of Micronesia are coral atolls and were under interim control of the United States through the Navy Military Government. They scatter over 770,000 square miles of ocean with a total land area of about 70 square miles. Two parallel chains of atolls form the Marshalls: Ratak (sunrise) to the east and Ralik (sunset) to the west (Figure V-1). Bikini and Enewetak Atolls in the northern end of the Ralik Chain were likely sites, and they were inhabited only by small communities of Micronesians. Bikini Atoll met all of the test site specifications; it is 2,500 miles west-southwest of Honolulu and 4,500 air miles from San Francisco; it is also easily accessible from operational military facilities on Kwajalein Atoll to the southeast and Enewetak (Eniwetok in 1946) to the west. Bikini Atoll's 162 inhabitants were moved to another atoll so that the nuclear weapons tests could be conducted.

Bikini (Figure V-2) is 189 nautical miles east of Enewetak. Its 26 named islets and sand spits constitute about 2.7 square miles of land that encircle a lagoon 25 miles long by 15 miles wide with a maximum depth of about 200 feet. About 53% of the area is in the eastern islands of Bikini and Eneu, and 24% is represented by the southern islands from Enidrik to Aerokoj. The detonation area for Operation Crossroads was in the northern 20% of the land area. Table V-1 lists the English code names along with the Marshallese names. Code names were assigned beginning with Able, Baker, Charlie, and proceeding in a clockwise fashion around the atoll. Letters Q and X were not used. Nuclear weapon test Able occurred on June 30, 1946 and was a 23 kiloton (KT) [1 KT = $4.2 \times 10^{12}$ joule] airburst over a target fleet. Test Baker on July 24, 1946 was a 23 kiloton underwater detonation in the Bikini Lagoon (NVO-209 1984). Both nuclear weapons were similar to the Nagasaki bomb. There were 93 target vessels in test Able and 92 vessels in test Baker. Test Able sank five ships and test Baker sank eight ships and several landing craft. Many

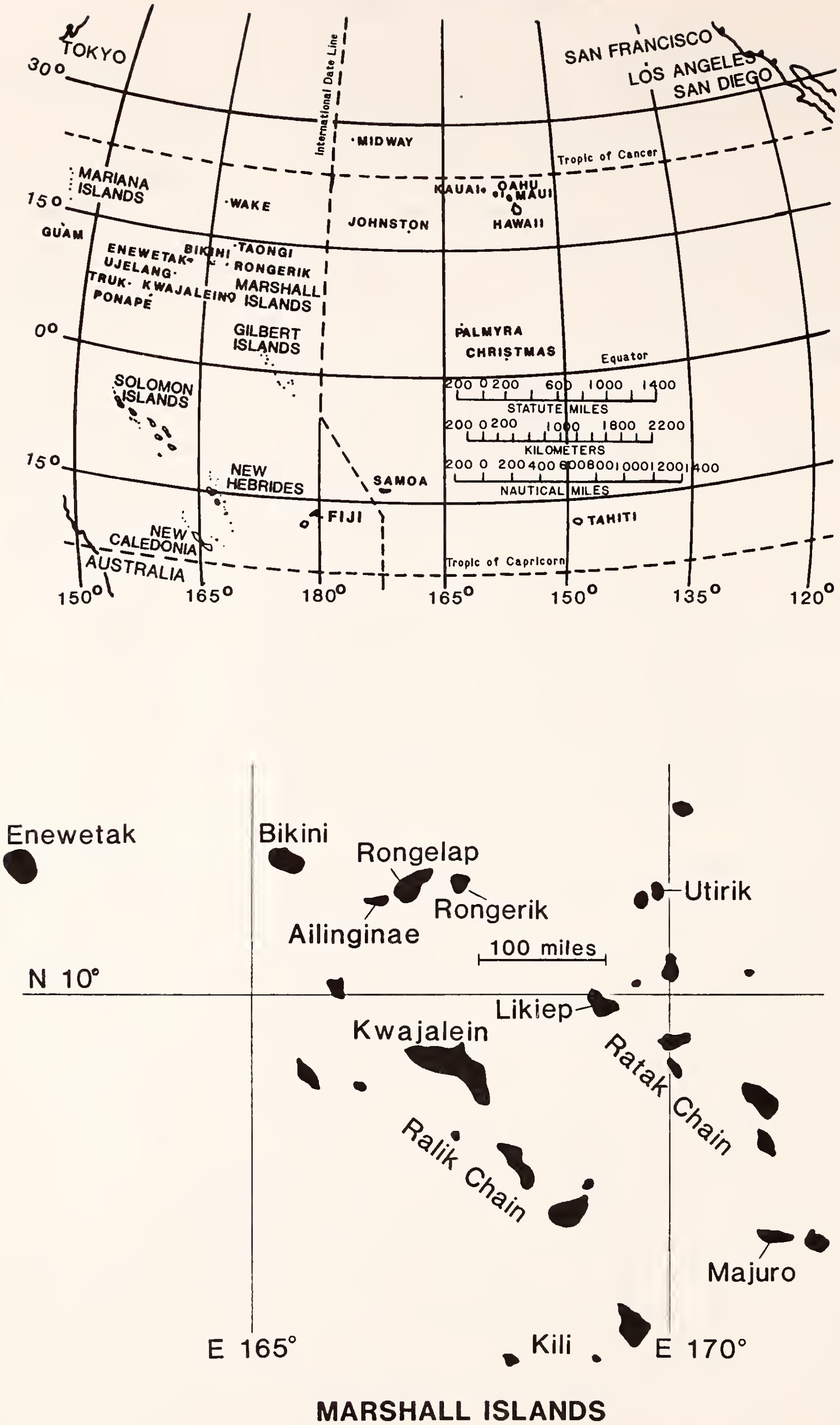



Figure V-1. Map of the Central Pacific showing location of the Marshall Islands and other important geographic sites including Johnston Island and Christmas Island (Martin and Rowland 1982; Conard et al. 1975).

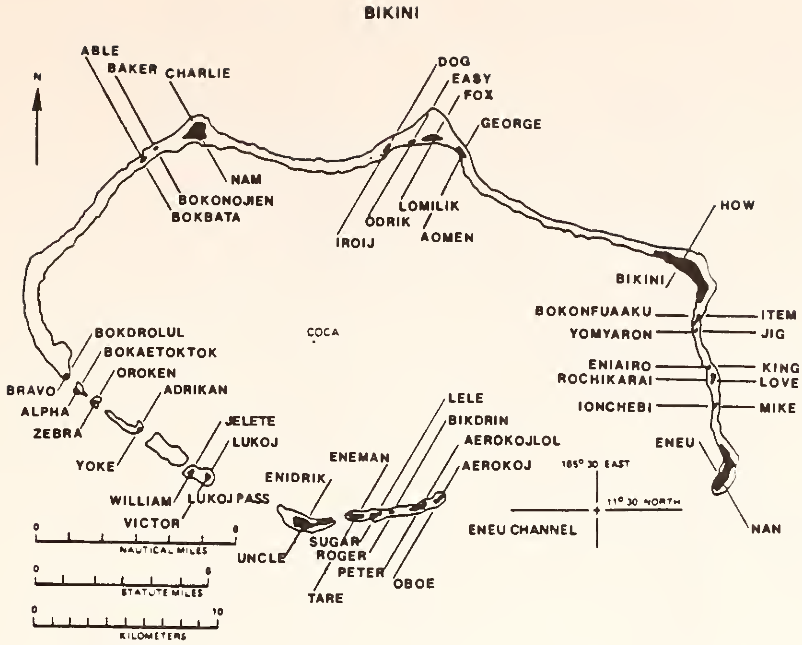



Figure V-2. Map of Bikini Atoll including the island's English code names (listed on the Seaward side) and Marshallese names (listed on the lagoon side) (adapted from Martin and Rowland 1982).

of the target vessels were damaged in both tests. Subsequently, Bikini was reduced to interim status for long-term observation.

Joint Task Force One was abolished on November 1, 1946 following tests Able and Baker at Bikini Atoll. The Atomic Energy Commission assumed the functions of the United States Army Corps of Engineers, Manhattan District, on January 1, 1947. The Commission was charged with responsibility for the total program of atomic energy development, including improvement of nuclear weapons and testing in the field. In July 1947, the Atomic Energy Commission established the Pacific Proving Grounds for routine experiments and tests of nuclear weapons. The Pacific Proving Grounds consisted of Enewetak and Bikini Atolls, their two lagoons and the waters within 3 miles of their seaward sides. The two atolls were part of the Trust Territory of the Pacific Islands, a Strategic Area Trusteeship of the United Nations administered by the United States through the Navy, followed by the Department of Interior and the Atomic Energy Commission. As a Strategic Area Trusteeship, the Trust Territory of the Pacific Islands was under the control of the United Nations Security Council, not the Trusteeship Council. Although the United States had de facto rule over the Trust Territory of the Pacific Islands, the United States never claimed de jure sovereignty over the area and the question of sovereignty was never determined, other than defining the United States as administrator (Branch 1980). Because of this, a constitutional dilemma exists in the Trust Territory of the Pacific Islands as to how to protect the customs and traditions of the people while at the same time providing the people with the same fundamental constitutional safeguards enjoyed by mainland citizens. Branch (1980) discussed the constitutional aspects of the Trust Territory of the Pacific Islands and presented arguments against the concept of Insular Cases which date back to 1898. Based on Branch's arguments,

Table V-1
English Code Names and Marshallese Equivalents
for Islands in Bikini Atoll[a]

| Code Name | Marshallese Name |
|---|---|
| Able | Bokbata |
| Baker | Bokonajien |
| Charlie | Nam |
| Dog | Iroij |
| Easy | Odrik |
| Fox | Lomilik |
| George | Aomen |
| How | Bikini |
| Item | Bokonfuaaku |
| Jig | Yomyaron |
| King | Eniairo |
| Love | Rochikarai |
| Mike | Ionchebi |
| Nan | Eneu |
| Oboe | Aerokoj |
| Peter | Aerokojlol |
| Roger | Bikdrin |
| Sugar | Lele |
| Tare | Eneman |
| Uncle | Enidrik |
| Victor | Lukoj |
| William | Jelete |
| Yoke | Adrikan |
| Zebra | Oroken |
| Alpha | Bokaetoktok |
| Bravo | Bokdrolul |

[a]Compiled from Martin and Rowland 1982.

citizens of the Trust Territory of the Pacific Islands would have equal protection under the constitution of the United States as do normal citizens. This has far-reaching implications as discussed later in this Section.

When selecting Enewetak as the next test site, all of the possibilities that had been examined during the earlier selection of Bikini were reviewed. A test site within the continental United States was initially considered desirable for establishing a permanent facility. A return to Bikini Atoll was not considered because Bikini was in interim status for long-term observation and the land areas of Bikini were neither large enough nor properly oriented to the prevailing winds to permit construction of a major airstrip. Potential sites in Alaska and the Indian Ocean were also studied, but Enewetak seemed to offer all of the advantages previously found at Bikini plus the presence of established airstrips and support facilities. The tentative selection of Enewetak was followed by an inspection of the atoll and conferences with leaders of the people of Enewetak.

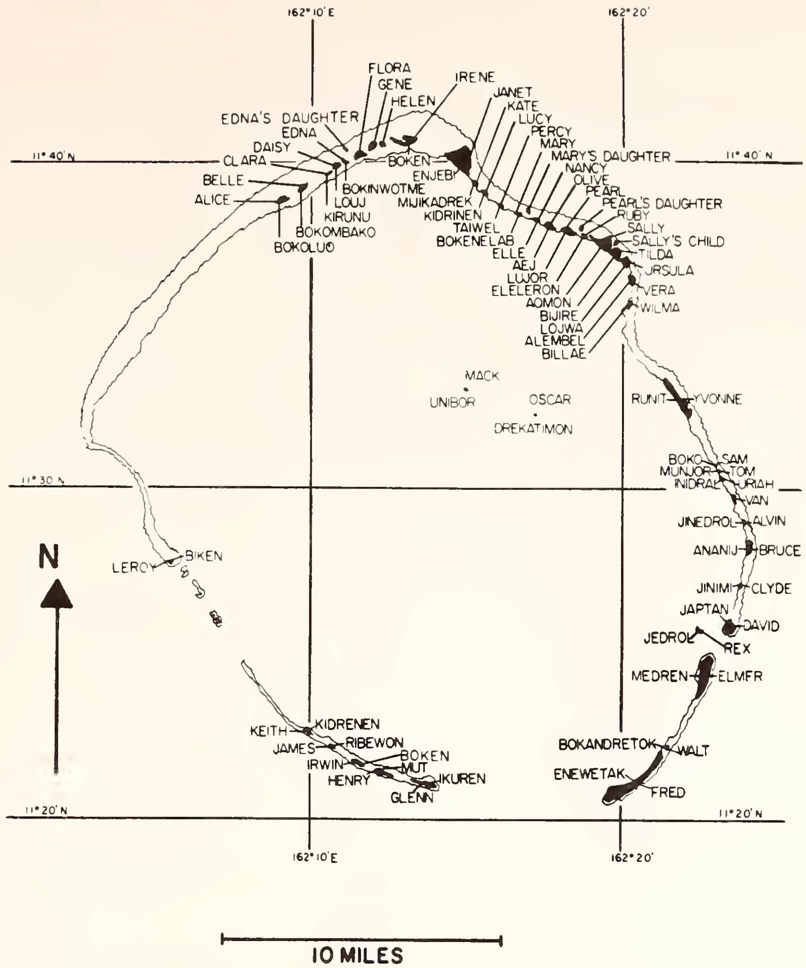



Figure V-3. Map of Enewetak Atoll including the island's English code names (listed on the seaward side) and Marshallese names (listed on the Lagoon side: Friesen 1982).

Enewetak (Figure V-3) is an elliptically shaped, low lying, coral atoll about 2740 miles west-southwest of Honolulu. The atoll enclosed a lagoon 23 miles in diameter with a total surface area of 388 square miles. Land area of the 46 islands and islets totals 2.75 square miles. In 1974, it was home to 145 Marshallese Islanders. The site was approved by President Truman on December 2, 1947 and the United Nations Security Council wa notified that, effective December 1, 1947, pursuant to the provisions of the Trusteeship Agreement, Enewetak Atoll was closed for security reasons so that necessary experiments relating to nuclear fission could be conducted. The Enewetak people were moved to a new home on Ujelang Atoll in December 1947. Ujelang Atoll, which is southwest of Enewetak, had been prepared to receive the Bikinians temporarily living elsewhere. The press release by the Atomic Energy Commission noted:

> "Eniwetok Atoll was selected as the site for the proving grounds after the careful consideration of all available Pacific Islands. Bikini is not suitable as the site since it lacks sufficient load surface for the instrumentation necessary to the scientific

observations which must be made. Of other possible sites, Eniwetok has the fewest inhabitants to be cared for, approximately 145, and, what is very important from a radiological standpoint, it is isolated and there are hundreds of miles of open seas in the direction in which winds might carry radioactive particles."

"The permanent transfer elsewhere of the Island people now living on Aomon and Bijiri Islands in Eniwetok Atoll will be necessary. They are not now living in their original ancestral homes but in temporary structures provided for them on the two foregoing islands to which they were moved by United States forces during the war in the Pacific, after they had scattered throughout the Atoll to avoid being pressed into labor service by the Japanese and for protection against military operations. The sites for the new homes of the local inhabitants will be selected by them. The inhabitants concerned will be reimbursed for lands utilized and will be given every assistance and care in their move to, and re-establishment at, their new location. Measures will be taken to insure that none of the inhabitants of the area are subject to danger; also that those few inhabitants who will move will undergo the minimum of inconvenience." (Richard, 1957, V. III, p. 553.).

After 1956, the Pacific Proving Grounds became known as the Enewetak Proving Grounds. The Test Division of the Atomic Energy Commission Division of Military Applications, Santa Fe Operations Office, administered the test site through its Enewetak Branch Office, which supervised engineering, construction, maintenance, operation, and management activities performed by its contractors.

The 46 islands and islets of Enewetak Atoll are shown in Figure V-3 with Marshallese names on the lagoon side and English code names on the ocean side (Friesen 1982). The assigned English code names begin with Alice, and proceed through the alphabet going clockwise around the atoll. Letters not used for female names included Q, X, and Z. Island Percy, in the northern sector between Lucy and Mary, was given a code name later than the other northern islands. Southern islands were assigned male codes names from Alvin through Oscar, then Rex through Walt; however, names were not assigned in a consistent clockwise order. Generally, the islands will be referred to by their English code names except for Enewetak Island. Table V-2 (Friesen 1982) lists other names or spellings that have appeared in various descriptions of the Marshall Islands.

Between 1946 and 1962, the United States conducted 109 atmospheric nuclear weapon tests in Oceanic regions. Sixty-six of these tests were conducted at the Pacific Proving Grounds between 1946 and 1958, and the remainder were conducted outside the original Pacific Proving Grounds (Table V-3).

Nuclear Weapons Tests at the Pacific Proving Grounds

After formal establishment of the Pacific Proving Grounds at Enewetak Atoll, the Atomic Energy Commission scheduled its first test series, called Sandstone, for the spring of 1948. Operation Sandstone consisted of three shots in April and May of 1948. All three were tower detonations related to weapons development and ranged in yield from 18 to 49 kilotons. The weapons used in Operations Sandstone were considerably different from weapons used at Trinity and in Operation Crossroads. They were detonated atop 200 ft steel towers, one each on islands Janet, Sally, and Yvonne. Operation Sandstone was a technical success and enabled the Commission to double the stockpile of nuclear weapons. The Mark 4 weapon tested in Operation Sandstone was the culmination of the shift from the laboratory to mass production of components and assembly-line techniques. Additionally, Sandstone tests confirmed that the growing stockpile of enriched $^{235}U$ could be used in implosion-type weapons which were much more efficient than gun-type weapons used previously (Los Alamos Science 1983).

On August 29, 1949, Russia detonated its first nuclear weapon. This news shocked the nation and touched off a debate within the United States Government over the possible development of a thermonuclear device. After the Atomic Energy Commission and National Security Council had considered the news, President Truman (on January 31, 1950) ordered the Commission to proceed with the development of all types of nuclear weapons including thermonuclear devices. On June 25, 1950, North Korea attacked South Korea and within a few days the United States had committed air,

Table V-2

Comparison of English Code and Native Names for Enewetak Atoll

| Site | Native Names From U.S. Hydrographic Office 1946 | Native Names From U.S. Hydrographic Office 1968 | From Bryan 1971 | From Tobin 1973 Native Names[a] |
|---|---|---|---|---|
| ALICE | Bogallua | Bogallua | Peony | BOKOLUO |
| BELLE | Bogombogo | Bogombogo | Petunia | BOKOMBAKO |
| CLARA | Ruchi | Eybbiyae | Poinsettia | KIRUNU |
| DAISY | b | Lidilbut | Primrose | LOUJ |
| EDNA[d] | b | b | Rambler | BOCINWOTME[c] |
| EDNA'S DAUGHTER | b | b | b | b |
| FLORA[d] | Elugelab | b | Sagebrush | b |
| GENE[d] | Teiteiripucchi | b | Sunflower | b |
| HELEN[d] | Bogairikk | Bogeirik | Violet | BOKAIDRIK |
| IRENE | Bogon | Bogon | Zinnia | BOKEN |
| JANET | Engebi | Engebi | Fragile | ENJEBI |
| KATE | Muzinbaarikku | Mujinkarikku | Arbutus | MIJIKADREK |
| LUCY | Kirinian | Billee | Aster Blossom | KIDRINEN |
| PERCY | b | b | b | TAIWEL |
| MARY | Bokonaarappu | Bokonarppu | Bitterroot | BOKENELAB |
| MARY'S DAUGHTER | b | b | Bluebonnet | b |
| NANCY | Yeiri | Yeiri | Buttercup | ELLE |
| OLIVE | Aitsu | Aitsu | Camellia | AEJ |
| PEARL | Rujoru | Rujiyoru | Canna | LUJOR |
| PEARL'S DAUGHTER | b | b | Carnation | b |
| RUBY[d] | Eberiru | Eberiru | Columbine | ELELERON |
| SALLY | Aomon | Aomon | Clover | AOMON |
| SALLY'S CHILD | b | b | Dandelion | b |
| TILDA | Biijiri | Biijire | Daisy | BIJILE[c] |
| URSULA | Rojoa | Rojoa | Delphinium | LOJWA |
| VERA | Aaraanbiru | Arambiru | Gardenia | ALEMBEL |
| WILMA | Piiraai | Piirai | Goldenrod | BILLAE |
| YVONNE | Runit | Runit | Hawthorn | RUNIT |
| SAM | b | b | b | BOKO |
| TOM | b | b | b | MUNJOR |
| URIAH | b | b | b | INEDRAL |
| VAN | b | b | b | b |
| ALVIN | Chinieero | b | b | JINEDROL |
| BRUCE | Aniyaanii | Japtan | Jasmine | ANANIJ |
| CLYDE | Chinimi | Chinimi | Lavender | JINIMI |
| DAVID | Japtan | Muti | Ladyslipper | JAPTAN |
| REX | Jieroru | Bogen | Lilac | JEDROL |
| ELMER | Parry | Parry | Heartstrings | MEDREN |
| WALT | b | b | b | BOKANDRETOK |
| FRED | Eniwetok | Eniwetok | Privilege | ENEWETAK |
| GLENN | Igurin | Igurin | Lantana | IKUREN |
| HENRY | Mui | Buganegan | Mimosa | MUT |
| IRWIN | Pokon | Bogan | Mistletoe | BOKEN |
| JAMES | Ribaion | Libiron | Oleander | RIBEWON |
| KEITH | Giriinien | Grinem | Oca | KIDRENEN |
| LEROY | Rigili | Rigile | Posy | BIKEN |
| OSCAR (coral head) | b | b | b | DREKATIMON |
| MACK (coral head) | b | b | b | UNIBOR |

[a]As confirmed by the Enewetak people during the Ujelang field trip of July 1973.

[b]No name reported.

[c]BOKINWOTME and BIJIRE are preferred according to current literature.

[d]Original island destroyed by nuclear tests except for small portions of EDNA, HELEN, and RUBY.

Table V-3

Announced Nuclear Weapons Tests Conducted by the United States in Oceanic Areas[a]

| | | | Location of Tests | | | | | | Type of Burst | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Operation | Tests | Year | Bikini | Enewetak | Johnston Island | Christmas Island | Pacific Ocean | Atlantic Ocean | Airdrop | Tower | Balloon | Surface | Barge | Under-water | Rocket Launched |
| CROSSROADS | 2 | 1946 | 2 | | | | | | 1 | | | | | 1 | |
| SANDSTONE | 3 | 1948 | | 3 | | | | | | 3 | | | | | |
| GREENHOUSE | 4 | 1951 | | 4 | | | | | | 4 | | | | | |
| IVY | 2 | 1952 | | 2 | | | | | 1 | | | 1 | | | |
| CASTLE | 6 | 1954 | 5 | 1 | | | | | | | | 2 | 4 | | |
| WIGWAM | 1 | 1955 | | | | | 1 | | | | | | | 1 | |
| REDWING | 17 | 1956 | 6 | 11 | | | | | 2 | 6 | | 3 | 6 | | |
| HARDTACK I | 35 | 1958 | 10 | 22 | 2 | | 1 | | | | 1 | 4 | 26 | 2 | 2 |
| ARGUS | 3 | 1958 | | | | | | 3 | | | | | | | 3 |
| DOMINIC I | 36 | 1962 | | | 10 | 24 | 2 | | 29 | | | | | 1 | 6 |
| TOTALS | 109 | | 23 | 43 | 12 | 24 | 4 | 3 | 33 | 13 | 1 | 10 | 36 | 5 | 11 |

[a]Compiled from NVO-209 1983.

naval, and ground forces to the Korean War. Nuclear weapon development was now sophisticated so that it was possible to plan smaller tests to resolve specific design problems. In addition, the Korean War had made the Enewetak Proving Grounds somewhat vulnerable in addition to being expensive in terms of military resources. From this point until the end of atmospheric testing, the Pacific Proving Grounds were used for large yield weapons tests in conjunction with other diagnostic tests and smaller yield weapons tests conducted at the Nevada Test Site.

As part of a series to test design principles for fission weapons, Operation Greenhouse was conducted at Enewetak Atoll in April and May of 1951. In addition to testing design principles for large-scale fission weapons, the Greenhouse series incorporated newer concepts of Teller and Ulam for the development of thermonuclear weapons. Operation Greenhouse produced the largest nuclear explosion up to that time (test George) and provided convincing proof of the soundness of the Teller/Ulman design for the hydrogen bomb. It was an expensive and complex series of tests that required approximately 2,580 scientists and technicians, and 6,000 military and civilian personnel, of which 2,768 were Navy personnel. Scientists quickly analyzed data from Operation Greenhouse in order to coordinate the final drive to develop thermonuclear weapons. The Atomic Energy Commission organized a conference at Princeton University in June of 1951 and scientists finally agreed that a thermonuclear weapon was possible.

Following the success of Operation Greenhouse, several supporting operations, Buster, Jangle, and Tumbler-Snapper, were conducted at the Nevada Test Site. Operation Buster was a 5-shot series in October and November 1951; Operation Jangle was a 2-shot series, also conducted in November of 1951. Operation Tumbler-Snapper consisted of eight low-yield weapon tests in 1952 conducted at the Nevada Test Site in preparation for large-scale operations at the Pacific Proving Grounds. As a result of these operations, the program for the development of thermonuclear weapons was well under way by the end of 1952 and culminated with Operation Ivy at Enewetak Atoll.

Operation Ivy consisted of two weapons tests. Shot Mike was the first test of an experimental thermonuclear device and was detonated on the surface of Island Flora (Elugelab) on Enewetak Atoll. All that remains of Island Flora is a crater in the reef about one mile across and 180 feet deep. Shot King was an airdrop burst at 1,500 feet elevation and was detonated over island Yvonne. Yields for the devices Mike and King were 10.4 megatons and 500 kilotons, respectively.

No tests were conducted at the Pacific Proving Grounds during 1953 while Operation Upshot-Knothole was being conducted at the Nevada Test Site. In 1954, Operation Castle was conducted with five tests detonated on Bikini Atoll and one on Enewetak. This was the first resumption of nuclear testing on Bikini Atoll since Operation Crossroads in 1946. All six tests in Operation Castle related to the development of thermonuclear weapons and had yields that ranged from 110 kilotons to 15 megatons. The first test in this series, Bravo, was detonated on March 1, 1954 on an island in the northern part of Bikini Atoll. Prior to the shot, it was anticipated to have a yield of approximately 5 megatons. However, the weapon actually exploded with a total yield in excess of 15 megatons and is the largest thermonuclear device to have been exploded by the United States. Bravo was to have unforeseen consequences for a number of people in the Marshall Islands because winds blew the fallout cloud to the east where 28 Americans and 239 Marshallese Islanders were exposed to significant levels of radiation. The Americans were on Rongerik Atoll. One hundred and fifty-seven (157) Marshallese were on Utirik Atoll, 64 were on Rongelap Atoll, and 18 Rongelap people were on the neighboring atoll of Ailinginae. In addition, a Japanese fishing vessel, the Daigo Fukuryu Maru (Fifth Lucky Dragon), located approximately 82 nautical miles from the Bravo detonation site with 23 fishermen aboard, was also exposed. The Marshallese on Rongelap Atoll were exposed to approximately 175 R; 69 R was the exposure to 18 individuals on Ailinginae Atoll; and 78 R was the exposure to American servicemen stationed on Rongerik. Utirik received a much lower exposure, 14 R to 157 Marshallese. Utirik Atoll was less

contaminated from the fallout than Rongelap, and was considered safe for habitation after a period of three months to allow for radioactive decay. Thus, the Utirik people returned with fresh supplies, clothing, and livestock. Rongelap Atoll was too contaminated to allow immediate return and its people, along with the 18 Rongelap citizens that were on Ailinginae Atoll, were taken to a temporary village built on Majuro Atoll. The Marshallese from Rongelap lived on Ejet Island in Majuro Atoll for three years, until they were allowed to return to their home islands. The remainder of Operation Castle consisted of four thermonuclear weapon tests on Bikini and one on Enewetak.

The next test series at the Pacific Proving Grounds was Operation Redwing in 1956. Operation Redwing was a 17-shot series that further advanced designs of nuclear weapons which produced reduced levels of radioactive fallout. The series consisted of six tests on Bikini and 11 on Enewetak. The second test in the series, Cherokee, was the first airdrop of a thermonuclear device by the United States. A continuing objective of all tests was to develop weapons of smaller size and weight with improved efficiency and safety in handling, and adapted to the needs of new weapons systems.

By 1956, worldwide concern for the potential health effects of nuclear weapons fallout was growing. The 1956 Presidential campaign debated the merits of a test ban. On March 31, 1958, the Soviet Union, after completing an extensive test series, announced a unilateral test ban and appealed to the other nuclear powers to halt their tests. After conferences in Geneva, on August 22, 1958, President Eisenhower announced that the United States would suspend testing for a year once test ban negotiations began. Even before this announcement, the Atomic Energy Commission had been testing at an urgent pace. Phase I of Operation Hardtack consisted of 35 detonations, held at the Pacific Proving Grounds and elsewhere in the Pacific. Ten tests were conducted at Bikini and 22 were held on Enewetak. Two devices in the megaton range were exploded at high altitude from rockets launched from Johnston Island. One low-yield, balloon-suspended detonation occurred just north of the Pacific Proving Grounds. The last test of Operation Hardtack I, Fig, was conducted on Enewetak on August 18, 1958. Fig and an earlier test, Quince, did not produce a nuclear yield and as a result contaminated island Yvonne (Runit) with plutonium. Fig was also the last test in the Marshall Islands. When the Soviet Union resumed atmospheric testing on September 1, 1961, the United States followed with extensive test series beginning on September 15, 1961 at the Nevada Test Site. All tests in the Pacific were conducted near Johnston Island or Christmas Island. After extensive testing by both the United States and the Soviet Union, an atmospheric test ban formally began on October 11, 1963.

Nuclear Weapons Tests at Other Oceanic Test Sites

Oceanic sites other than the Marshall Islands were used for nuclear weapons testing under the authority of the Atomic Energy Commission (Table V-4). A total of 43 test detonations were conducted at these sites with 24 tests occurring at Christmas Island and 12 tests in the Johnston Island area. Johnston Island is about 725 miles west-southwest of Hawaii. Christmas Island, the largest island in the central Pacific, is in the Line Islands Archipelago about 1350 miles south of Hawaii. Johnson Island is a possession of the United States; Christmas Island was claimed by Great Britain and the United States. During this period of atmospheric testing, the United States acceded to Great Britain's claim.

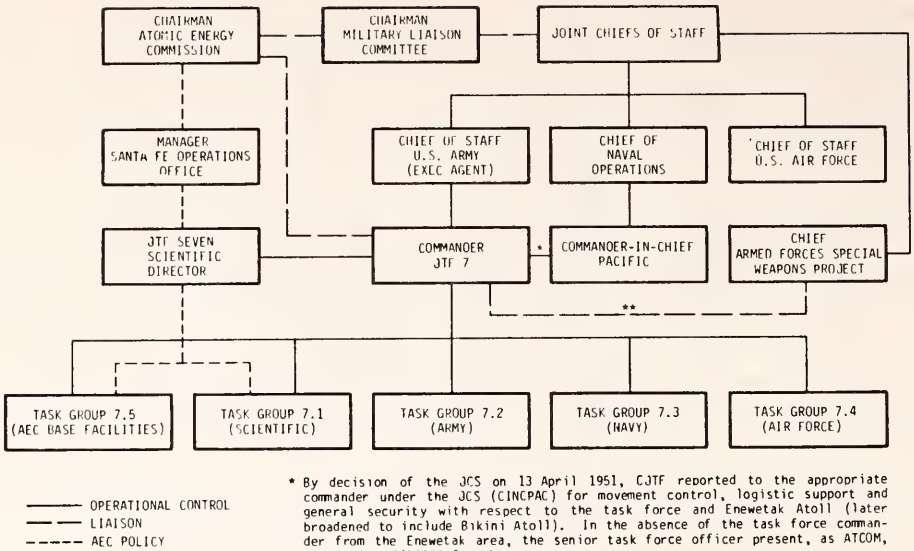
Tests in open ocean areas were also conducted. Two tests were conducted about 500 miles southwest of San Diego, California. Operation Wigwam consisted of a single 30 kiloton underwater nuclear device detonated at N 29°, W 126° on May 14, 1955 (Weary et al. 1981). During Operation Dominic I, shot Swordfish on May 11, 1962 was an antisubmarine rocket launch that resulted in a low-yield (< 20 kiloton) underwater detonation at N 31° 14', W 124° 13'. Also during Operation Dominic I, shot Frigate Bird on May 6, 1962 was a rocket-launched nuclear weapon from a Polaris submarine detonated at N 4° 50', W 149° 25'.

Table V-4

Oceanic Nuclear Weapons Tests Conducted Outside the Pacific Proving Grounds (PPG) by the United States[a]

| Operation Name | No. of Tests | Year | Location | Yield | Test Type |
|---|---|---|---|---|---|
| WIGWAM | 1 | 1955 | ~ 500 mi SW of California N 29°, W 126° | 30 Kiloton | Underwater |
| HARDTACK I | 2 | 1958 | Johnston Island Area | Megaton | Rocket launched, high altitude |
| HARDTACK I | 1 | 1958 | Near the PPG N 12° 37', E 163° 01' | - | Balloon |
| ARGUS | 3 | 1958 | South Atlantic | 1-2 Kiloton | Rocket launched, 300 mi altitude |
| DOMINIC I | 24 | 1962-63 | Christmas Island Area | < 20 Kiloton Megaton | Airdrop |
| DOMINIC I | 10 | 1962-63 | Johnston Island Area | < 20 Kiloton | Airdrop (5) and Rocket launched (5) |
| DOMINIC I | 2 | 1962 | Near N. America, N 31° 14', W 124° 13' | Low | Antisubmarine rocket launched, underwater |
| | | | E. of Christmas Island N 4° 50', W 149° 25' | - | Polaris submarine rocket launch |

[a]Source NVO-209 1983.




* By decision of the JCS on 13 April 1951, CJTF reported to the appropriate commander under the JCS (CINCPAC) for movement control, logistic support and general security with respect to the task force and Enewetak Atoll (later broadened to include Bikini Atoll). In the absence of the task force commander from the Enewetak area, the senior task force officer present, as ATCOM, reported to CINCPAC for these purposes.

** By decision of the JCS on 23 April 1953, the Chief AFSWP exercised, within any task force organization, technical direction of the weapon effects tests of primary concern to the Armed Forces at atomic tests conducted outside the continental United States. Prior to the onsite phase of an overseas test operation, the task force consulted the Chief AFSWP on modifications or deletions to the DOD weapon effects test programs.

Figure V-4. Diagram showing lines of authority and organization of Joint Task Force Seven (Martin and Rowland 1982).

Three other Oceanic tests were conducted during Operation Argus in 1958 in the South Atlantic. The Argus tests consisted of three-stage rocket-launched weapons, 1-2 kiloton detonated at high altitudes (~ 480 km) to test the effects of charged particles produced by nuclear weapons on communications. Operation Argus involved approximately 4,500 men aboard nine ships and did not result in significant radiation exposures over background to the test personnel (Jones et al. 1982). Several rocket-launched nuclear weapon tests from the Johnston Island area were aborted with non-nuclear detonations of their chemical explosives resulting in dispersion of the fissile components (NVO-209 1984).

Early Authority to Test Nuclear Weapons

Operation Crossroads in 1946 was conducted under the authority of Joint Task Force One which was composed of elements of the armed services, civilian contractors, technicians, and scientists under a military commander. Authority to test was directly delegated to Joint Task Force One from President Truman (Shurcliff 1974). All other nuclear weapons tests conducted by the United States have been conducted under civilian authority of the Atomic Energy Commission. Because of the long distances involved, logistics, transportation and security, individual Task Forces were placed under a military command which was responsible for coordinating the activities of the four armed services and civilians from private contractors and nuclear weapons laboratories.

For Oceanic tests between 1948 and 1962, the Atomic Energy Commission delegated operational authority to the military commanders of the Joint Task Forces. An example is shown in Figure V-4, which is the organizational chart for Joint Task Force Seven that conducted Operation Castle at the Pacific Proving Grounds during 1954 (Martin and Rowland 1982). A copy of a letter

UNITED STATES
ATOMIC ENERGY COMMISSION
WASHINGTON 25, D. C.

IN REPLY REFER TO

MAT:NDG

JAN 2 1 1954

Major General P. W. Clarkson, USA
Commander, Joint Task Force SEVEN
Temporary "U" Building, Room 2005
12th and Constitution Avenue, N. W.
Washington 25, D. C.

Dear General Clarkson:

Presidential approval has been received for executing CASTLE with March 1, 1954 as the starting date. Permission has also been granted to detonate seven shots and to expend fissionable and fusionable materials in the amounts indicated below.

This letter should be construed as your authority to execute CASTLE as planned.

Sincerely yours,

K. D. Nichols

K. D. Nichols
General Manager

Enclosure:
Cys 1A & 2A Fissionable and Fusionable
Material For CASTLE Devices

Figure V-5. Letter of Approval from the general manager of the Atomic Energy Commission to the Commander of Joint Task Force Seven indicating that Presidential approval was received.

acknowledging receipt of Presidential approval sent by the general manager of the Atomic Energy Commission to the commanding officer of Joint Task Force Seven is shown in Figure V-5. In Figure V-5, the spaces preceding the last sentence are deleted because they contained classified information that referred to masses of fissile, fissionable, and fusionable materials to be expended in the tests. Thus, Presidential authority for the Oceanic Nuclear Weapons Tests was

delegated to civilian control via the Atomic Energy Commission through the manager of the Santa Fe Operations and then to Joint Task Force Scientific Directors and to the Commander of Joint Task Forces thereby satisfying the Congressional mandate for civilian control of nuclear weapons. Beginning with Operation Castle in 1954, Joint Task Force Seven was designated a permanent organization and conducted all test series in the Pacific until formation of Joint Task Force Eight in 1961 to conduct the Dominic series. Naval Task Force 88 conducted Operation Argus in the South Atlantic in 1958.

Radiological Safety

Radiological safety has always been a major part of nuclear weapons testing dating back to Trinity in 1945. From Operation Sandstone in 1948 through the period of atmospheric testing which ended in 1963, radiation exposure criteria were based on Atomic Energy Commission industrial safeguards. For example, during Operation Ivy in 1952, two types of radiological safety standards were used: a maximum permissible exposure, which related to an individual's accumulated whole-body exposure over the entire operation, and a maximum permissible limit, which referred to the amount of radioactive contamination allowed to remain on equipment or personnel. Radiological safety criteria based on Atomic Energy Commission industrial standards were approved by the Surgeon Generals of the Army and Air Force, Chief of the Navy Bureau of Medicine and Surgery, and the Director of the Atomic Energy Commission, Division of Biology and Medicine.

At the time of Operation Ivy, the distinction between exposure and dose was not usually made. All records express measured data in exposure units [roentgens, R]. The exposure standard used by the Commander of Joint Task Force 132 for the duration of Operation Ivy was a maximum permissible exposure of 3 R (Gladeck et al. 1982). However, this limit was later modified because the industrial standard at that time was 15 R, and assuming 2 weeks vacation per year, the quarterly standard became 3.9 R. The military maximum permissible exposure for whole-body exposure was 0.3 R per week, but the level recommended for routine operations was 0.05 R or less per 24-hour period. If an individual exceeded 0.3 R/week, he was removed from further exposure until his total exposure averaged less than 0.3 R/week. The 0.3 R/week criterion was also the Atomic Energy Commission's criterion for industry.

If an individual was assumed to work with radioactive materials for less than 2 years, different limits applied. These individuals were allowed to accumulate 1.25 R/month. The yearly limit was smaller (15 R vs 15.6 R based on the 0.3 R/week criterion), but this limit could be received in a single exposure, if no additional exposure occurred during that month. A third operational limit applied to accidents or for individuals not subjected to routine exposure. The "emergency" maximum permissible exposure was 5 R for one event, if a total of 15 R/year was not exceeded.

All of these exposure limits were based on recommendations of the National Committee on Radiation Protection. The National Committee on Radiation Protection reduced the recommended exposure rate from 0.1 R/day to 0.05 R/day in 1945, not because the older value was found unsafe, but because the nature of radiation in the weapons testing programs was more penetrating than the medium-energy X-rays on which the older value was established (Gladeck et al. 1982; Taylor 1971). The new exposure limit was designed to result in the same dose to bone marrow as the older maximum permissible exposure. Thus, whole-body radiation exposure limits for tests conducted during Operation Crossroads in 1946 and Operation Sandstone in 1948 were about twice as high as for Operation Ivy and subsequent Oceanic tests.

Maximum permissible limits for Operation Ivy were identical to United States Navy standards (Nav Med P-1325 1951) which stated:

Permissible contamination levels stated below are to be regarded as advisory limits for the general guidance of Rad-Safe Personnel attempting control of contamination under average conditions. These limits may be adjusted upward or downward under special circumstances, as directed by CTG 132.1.

All readings of contamination levels are to be made with side-window G-M counters, the counter tube walls of which are not substantially in excess of 30 mg/cm$^2$ with the beta shield open. When possible, the surface of the probe should be held 1 to 6 in. from the surface under observation. The larger distance is preferable for preliminary survey; the smaller distance is preferable for detailed survey of maximum contamination areas.

Personnel and Clothing

Skin: Complete decontamination by bathing is to be attempted. If a reading in excess of 1 mr/hr is obtained after repeated washings, the decontamination supervisor will be consulted for appropriate advice.

Underclothing and Body-contact Equipment (Interior Linings of Boots and Respirators): The permissible limit is 2 mr/hr.

Outer Clothing and Body-proximity Equipment (Outer Surface of Boots and Protective Clothing): The permissible limit is 7 mr/hr.

Aircraft, Vehicles, and Small Boats

The permissible limits are as follows: interior surfaces, 2 mr/hr; exterior surfaces, 7 mr/hr; and distant exterior surfaces, 20 mr/hr.

Air and Water

The following continuous levels of radioisotope content in air and water are generally considered to be safe:

| | Beta or gamma emitter | Alpha emitter |
|---|---|---|
| Air | $10^{-9}$ μc/cc | $5 \times 10^{-12}$ μc/cc |
| Water | $10^{-7}$ μc/cc | $10^{-7}$ μc/cc |

Note: The abbreviation "c" was commonly used in 1952 to represent "curie;" the currently used abbreviation is Ci. Similarly, "cc" means "cubic centimeter;" cm$^3$ is currently used.

As techniques developed for cloud sampling, pilot safety became a major concern. Previous experience in the use of the jet-powered F-84G airplanes for cloud sampling was confined to the Nevada Test Site during Operations Buster and Jangle in 1951, and during Operation Tumbler-Snapper in early 1952. Nuclear fission yields for these tests ranged from 0.1 to 31 kiloton (NVO-209 1984). The first test of Operation Ivy, shot Mike was anticipated to have a yield ranging from 4 to 10 megatons or about 500 times the yield of the Nagasaki bomb. This high yield was expected to result in much larger exposures to sampler aircraft pilots. After discussion with Atomic Energy Commission officials, the Surgeon General of the Air Force and other responsible officials, it was recommended that a one-time only emergency exposure limit of 20 R be approved. However, Los Alamos scientists suggested that an exposure of 100 to 125 R could be experienced by unprotected pilots. For this reason and to enable participation in multiple tests, protective clothing was designed for sampler pilots equivalent to 0.5 mm lead. The postulated 20 R integrated whole-body exposure was subject to the following restrictions (Gladeck et al. 1982).

1. Personnel in the special category of 20 R allowable exposure would be the pilots of the F-84G sampler aircraft;
2. Personnel in the special category would be allowed a total exposure of 20 R for the entire Operation Ivy;
3. Personnel who received the maximum of 20 R would not be re-exposed to a similar "one-shot" exposure of this extent for at least 2 years; this was not to preclude additional exposures on a lifetime basis of 0.3 R per week;

4. Suitable medical records of such individuals would be maintained in their parent agencies to reflect the exposures to ensure compliance with the 20 R restrictions;
5. Personnel expected to be in the 20 R category would be given the special radsafe physical examination before exposure and at least once per year for 2 years after the exposure period;
6. Results of medical examinations would be reported by the respective Department of Defense services, or sponsoring agency if non-military, and to the AEC with suitable identifying data to maintain a central repository for exposure records of all personnel involved in atomic tests of the AEC.

Atomic Energy Commission approval was granted to the Commander of Joint Task Force 132 giving the authority to permit an upper limit of 25 R (whole-body) exposure and recommended that sampler pilots receiving this maximum not be used in subsequent operations involving more than normal permissible exposures to radiation unless their services were required to avert an imminent threat to national security. At least one other special radiation limit was established. Task Group 132.4 of the Air Force was responsible for the Weather Reconnaissance Element and used an exposure rate of 9 R/hr as the maximum exposure rate for personnel in its airborne WB-29 aircraft.

Medical opinion concerning health risks from ionizing radiation at the time of Operation Ivy in 1952 is illustrated by the following (from Nav Med P-1325, 1951, Radiological Safety Regulations);

> Although the term "tolerance" is used in reference to dosage of radiation, there is no proof that living tissues are completely tolerant to ionizing radiation even in the minute amounts everywhere present as normal background radiation (cosmic rays, radon, et cetera). The term "Maximum Permissible Exposure", is a better term. Accordingly, the word "tolerance" will be replaced by the term "Maximum Permissible Exposure (MPE)".
>
> The MPEs do not represent limits within which there can be a complete disregard of exposure. The exposure to ionizing radiation should be kept to an absolute minimum in all circumstances.

As is apparent, concepts guiding radiological safety in 1952 were similar to the present day "ALARA" concept (As Low As Reasonable Achievable).

Responsibility for radiological safety during oceanic weapons testing was a command function. Figures V-6, V-7, and V-8 show the chain of command and lines of responsibility for radiological safety during Operation Ivy. Figure V-6 shows the organization of Joint Task Force 132 and the delegation of authority from the Atomic Energy Commission. Figure V-7 shows the organization of Scientific Task Group 132.1 which contained Task Unit 132.1.7, the unit directly responsible for radiological safety. The organizational structure of Task Unit 132.1.7 is shown in more detail in Figure V-8. It was directly responsible to the Deputy Commander of Joint Task Force 132 for Scientific Matters and ultimately to Commander, Joint Task Force 132. Details on day-to-day operational activities of the radiological safety organization are discussed by Gladeck et al. (1982).

Radiation exclusion, or radex, areas were established for Oceanic Nuclear Weapons Tests by the United States Air Force in Task Group 132.4 (Figure V-6). These were to prevent people from being too close to the detonation site and being over-exposed to radiation. For the thermonuclear test Mike, the final radiation exclusion area was decided only shortly before shot time based on forecasts of winds up to 3 hours post-detonation and meteorological data up to 60,000 feet altitude. Although an exact description of the radiation exclusion area was not available (Gladeck et al. 1982), a de facto radiation exclusion area was established by the security perimeter. Persuant to the terms of the Trust Agreement, the United States established a danger zone around the Atoll for an indefinite period. This danger zone included an area of 150 by 200

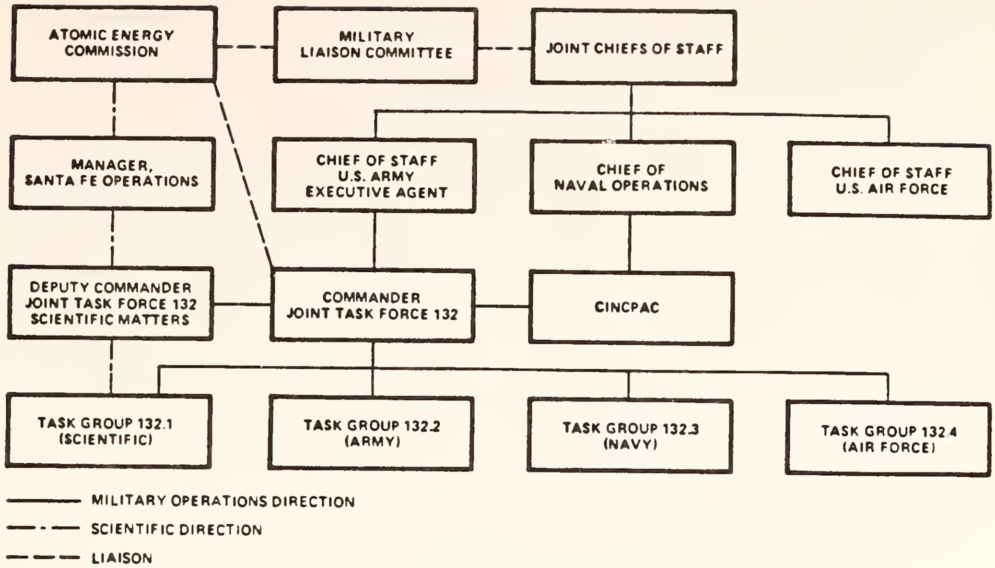



Figure V-6. Diagram showing lines of authority and organization of Joint Task Force 132 (adapted from Gladeck et al. 1982).

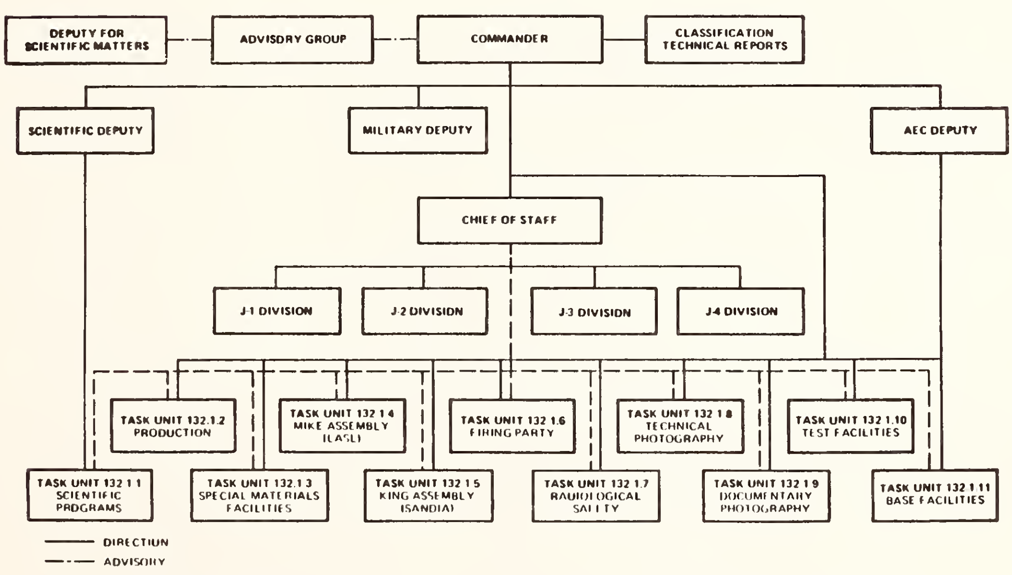



Figure V-7. Diagram showing lines of authority and organization of Task Force 132.1, Ivy (Gladeck et al. 1982).

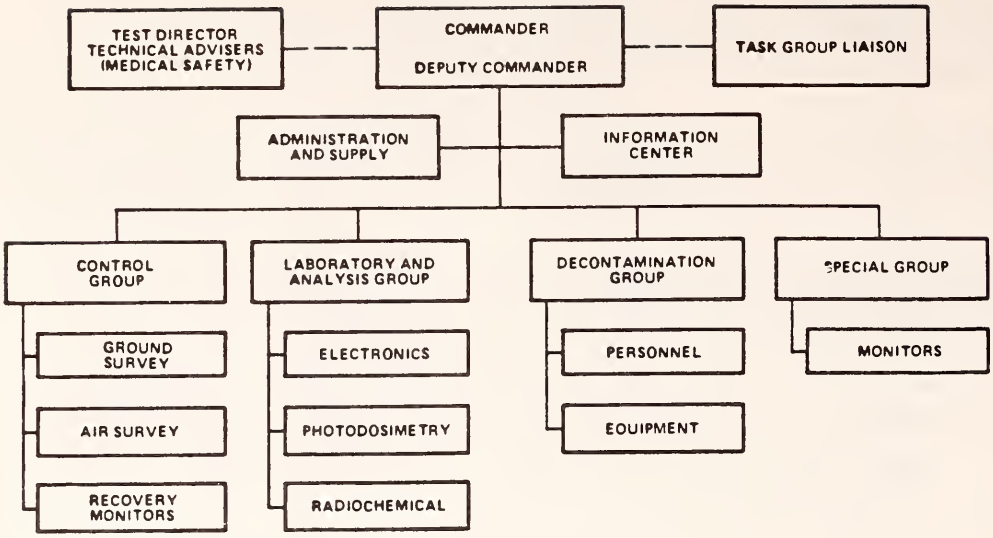



Figure V-8. Diagram showing lines of authority and organization of the radiological safety organization of Task Unit 132.7, Ivy (Gladeck et al. 1982).

nautical miles, centering on Enewetak Atoll, and bounded by the parallels of 10° 15' N and 12° 45' N and meridians 160° 35' E and 163° 55' E.

Early in the radiological safety planning for Operation Ivy, the safety of non-task force civilians was addressed. The adopted safety measures included preshot evacuation of Marshallese closest to the detonation site, measurement of fallout throughout the Marshall Islands, and development of a worldwide network of fallout-recording stations. Drinking water was also analyzed at nearby atolls. For shot Mike, all Task Force personnel were evacuated from Enewetak Atoll to United States Navy ships off Enewetak. Former Marshallese residents of Enewetak living on Ujelang Atoll (about 150 nautical miles to the southwest) were evacuated prior to the Mike shot. Plans were also formulated for emergency evacuation of Task Force personnel from both Bikini and Kwajalein Atolls if fallout was likely to head in their direction. After a post-detonation radiological survey of Ujelang found no radioactivity above background, people were returned to their homes on Ujelang Atoll.

Personnel exposures during Operation Ivy were determined from both pocket dosimeters and film badges. A total of 5,000 film badges were issued, but the intent was to issue badges only to people who might enter contaminated areas or be exposed to fallout. Since the total number of participants in Operation Ivy was about 11,650, some of the exposures had to be reconstructed from combinations of records of assignments, film badges, and pocket dosimeter readings (Gladeck et al. 1982). Special provisions were made for decontaminating ships and aircraft. These included installation of "washdown" systems aboard ships to prevent accumulation of fallout and installation of filters on aircraft intakes leading to pressurized crew compartments.

Two types of shipments were used in transporting materials from the Pacific Proving Grounds to the United States. If materials were to be shipped by common carrier, Interstate Commerce Commission regulations applied. Sometimes this required a long-term holding period for decay of radioactivity to allowable levels. If operational requirements did not permit this decay period,

courier service was used that was not subject to Interstate Commerce Commission regulations. However, these courier shipments had to comply with Joint Task Force 132 regulations on transport of radioactive materials.

Radiation Exposures to Weapons Test Participants

Radiation exposures received by United States Navy personnel participating in Oceanic Nuclear Weapons Tests conducted by the United States are shown in Table V-5. All data were part of the Navy's contribution to the Nuclear Testing Personnel Review and were summarized by Grissom et al. (1983). Navy personnel accounted for almost half of the total participants in the Oceanic Nuclear Weapons Tests. Operation Crossroads in 1946 resulted in a mean personnel exposure of 0.19 R with one individual receiving 3.17 R. Because all personnel were not given film badges, the listed exposures are made up of individual film badge exposures, assigned fallout exposures, and reconstructured film badge equivalent exposures. Film badges were only issued to those who were expected to be exposed to ionizing radiation as a result of their assignments. This practice was followed for the subsequent nuclear weapons tests in Operations: Sandstone in 1948, Greenhouse in 1951, and Ivy in 1952. During most of Operation Castle in 1954 and subsequent test series, there was an attempt to issue film badges to all participants.

The three shots of Operation Sandstone in 1948 resulted in a mean exposure to 7,299 Navy personnel (1,873 badged) of 0.024 R with the highest recorded exposure being 5.14 R. Relatively few Navy personnel aboard ships were issued film badges. During April and May of 1951, Operation Greenhouse was conducted at Enewetak Atoll with 2,899 Navy and Navy-affiliated personnel as participants of which 2,152 were badged. The mean exposure was 1.16 R, but 66 people received exposures in excess of the current limit of 5 R. Four persons were in the 10 to 25 R group with a mean of 17.7 R. Including Operations Sandstone and Greenhouse, a total of 67 people received exposures greater than the current limit of 5 R.

Operation Ivy, a two-shot test series conducted at Enewetak in 1952, consisted of the first thermonuclear test, Mike, rated at 10.4 megatons yield, and King a 500 kiloton device. Even though Mike was hundreds of times more powerful than previous tests at the Pacific Proving Grounds, relatively low personnel exposures resulted due to the extensive radiological safety program that was adopted. The total number of participants in Operation Ivy was 11,650 of which about 2,700 were military personnel on Kwajalein Atoll, 360 nautical miles to the southeast (Gladeck et al. 1982). Naval personnel totaled 5,251 among which 870 were issued film badges. As shown in Table V-5, the mean exposure for Navy personnel was 0.144 R with only one person over the Joint Task Force 132 recommended maximum permissible exposure of 3.9 R. Very few other men exceeded this exposure limit and they were involved in two aircraft accidents.

The first accident that resulted in the highest exposure recorded, involved the crew of a search and rescue aircraft that was responding to an emergency. A sampler jet aircraft and its pilot went down near Enewetak Island soon after Mike. The search and rescue aircraft flew directly to the last reported position, passing through a fallout zone. As a result, the 7-man crew received exposures of 10 to 17.8 R. The second group of overexposures occurred when a 12-man photographic aircraft arrived early at the Mike crater and was subjected to a high level of radiation from residual radioactivity. The crew members received exposures ranging from 8.6 to 11.6 R. From 1946 through 1952, 11 nuclear weapons tests at the Pacific Proving Ground resulted in 86 persons receiving more than 5 R.

Operation Castle, conducted in 1954, was originally scheduled to be a 7-shot series at the Pacific Proving Grounds (Martin and Rowland 1982). However, because of problems associated with the first test and delays in subsequent tests only 6 shots were detonated. The Castle series was held to test large yield thermonuclear or hydrogen weapons. Development of thermonuclear devices

Table V-5

Summary of Exposures to Naval Personnel in Oceanic Nuclear Weapon Tests Conducted by the United States[a]

| Operation | No. of Tests | Year | Location | Mean Exposure (mr) | Total Navy Personnel | | Exposure Range (mr) 0 | 1–500 | 500–1000 | 1000–2000 | 2000–3000 | 3000–4000 | 4000–5000 | 5000–10000 | 10000–25000 | >25000 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CROSSROADS | 2 | 1946 | Bikini Atoll | 193 | 10725 | Personnel in each group | 5707 | 3246 | 795 | 975 | 1 | 1 | | | | |
| | | | | | | Group mean exposure (mr) | 0 | 87 | 800 | 1179 | 2158 | 3167 | | | | |
| SANDSTONE | 3 | 1948 | Enewetak Atoll | 24 | 1865 | Personnel in each group | 1675 | 165 | 13 | 10 | 0 | 1 | 1 | | | |
| | | | | | | Group mean exposure (mr) | 0 | 85 | 750 | 1367 | 0 | 3645 | 5140 | | | |
| GREENHOUSE | 4 | 1951 | Enewetak Atoll | 1163 | 2768 | Personnel in each group | 406 | 637 | 268 | 1099 | 153 | 75 | 64 | 62 | 4 | |
| | | | | | | Group mean exposure (mr) | 0 | 309 | 790 | 1332 | 2356 | 3536 | 4463 | 5894 | 17661 | |
| IVY | 2 | 1952 | Enewetak Atoll | 144 | 870 | Personnel in each group | 227 | 584 | 20 | 27 | 11 | 0 | 1 | | | |
| | | | | | | Group mean exposure (mr) | 0 | 77 | 707 | 1360 | 2288 | 0 | 4120 | | | |
| CASTLE | 6 | 1954 | Enewetak Atoll (1) | 1530 | 7665 | Personnel in each group | 105 | 3266 | 1436 | 1245 | 682 | 372 | 252 | 191 | 113 | 3 |
| | | | Bikini Atoll (5) | | | Group mean exposure (mr) | 0 | 366 | 709 | 1506 | 2459 | 3498 | 4477 | 6632 | 18325 | 96773 |
| WIGWAM | 1 | 1955 | Pacific Ocean | 8 | 6549 | Personnel in each group | 6108 | 439 | 1 | 1 | | | | | | |
| | | | N 29°, W 126° | | | Group mean exposure (mr) | 0 | 120 | 960 | 1076 | | | | | | |
| REDWING | 17 | 1956 | Enewetak Atoll (11) | 804 | 6430 | Personnel in each group | 842 | 1973 | 1843 | 1257 | 290 | 154 | 52 | 19 | | |
| | | | Bikini Atoll (6) | | | Group mean exposure (mr) | 0 | 259 | 745 | 1352 | 2459 | 3443 | 4407 | 5831 | | |
| HARDTACK I | 35 | 1958 | Bikini Atoll (10) | 568 | 8350 | Personnel in each group | 1011 | 3428 | 2538 | 1218 | 131 | 18 | 4 | 2 | | |
| | | | Enewetak Atoll (22) | | | Group mean exposure (mr) | 0 | 251 | 708 | 1389 | 2295 | 3471 | 4565 | 5647 | | |
| | | | Johnston Island Area (2) | | | | | | | | | | | | | |
| | | | Pacific Ocean (1) | | | | | | | | | | | | | |
| ARGUS | 3 | 1958 | South Atlantic | 0 | 4456 | Note: (b) | | | | | | | | | | |
| DOMINIC I | 36 | 1962 | Christmas Island Area (24) | 90 | 15932 | Personnel in each group | 7532 | 7954 | 136 | 200 | 102 | 3 | 4 | 1 | | |
| | | | Johnston Island Area (10) | | | Group mean exposure (mr) | 0 | 96 | 721 | 1435 | 2419 | 3595 | 4257 | 6000 | | |
| | | | Pacific Ocean (2) | | | | | | | | | | | | | |

[a] Compiled from Grissom et al. 1983.

Note (b) All three tests in Operation ARGUS were rocket launched, 300 mile altitude bursts and resulted in no measured exposures to navy personnel.

had been in progress since 1951. During Operation Ivy in 1952, the Mike shot was the first device to generate a substantial fraction of the potential explosive yield from the result of fusion of deuterium and tritium.

The Mike shot did not involve a deliverable weapon because it weighed 140,000 lbs not including the cryogenics unit (Los Alamos Science 1983). Although none of the Castle series shots were air dropped, some of the devices tested were capable of being air dropped. The first shot scheduled in the Castle series, Bravo, was anticipated to have a yield of about 5 megatons. Based on experience with the Mike shot in 1952, plans were made to reduce personnel exposures by a variety of means. Elaborate procedures were adopted for cloud sampling and sample handling (Martin and Rowland 1982). As the Bravo shot approached, Joint Task Force 7 staff began closer monitoring of weather forecasts. A series of command briefings was held beginning about 36 hours prior to scheduled shot time (0645, March 1, 1954). At 18 hours before the scheduled shot time, the task force predicted, "no significant fallout for the populated Marshalls" (Martin and Rowland 1982). At the midnight preshot briefing, winds at 20,000 ft altitude were blowing toward Rongelap Atoll, but at such low velocity that no significant fallout was predicted for the populated Marshall Islands to the east. Bravo was detonated at 0645 with an explosive yield estimated to be 15 megatons. Because Bravo had about three times the expected yield, the fallout cloud penetrated the tropopause and encountered unanticipated high velocity, high altitude winds that carried radioactive debris eastward toward populated Marshall Islands.

All personnel on Bikini Atoll with the exception of a small firing party in a shielded bunker on Nan (Eneu) had been evacuated by the fleet which had taken up positions ranging from 30 to 50 nautical miles south of the Atoll (Martin and Rowland 1982). By 0800, the closest ships began encountering fallout. Remote sensing devices on Tare (Eneman) indicated high levels of fallout with an exposure rate of 250 R/hr on Eneman and Eneu. This high level contamination required abandoning plans to use the southern islands of Bikini Atoll as a post-shot staging area for activities associated with Bravo and other subsequent shots. For the remainder of Operation Castle, all personnel were required to stay aboard the fleet and access to the islands of Bikini Atoll was strictly controlled (Martin and Rowland 1982).

The cloud of radioactive debris from Bravo quickly reached the tropopause and began drifting eastward (Figure V-9). Three important human exposures to fallout in offsite areas occurred. Table V-6 lists the total exposures that resulted from Operation Castle including shot Bravo. Martin and Rowland (1982) estimate that Bravo accounted for about half of the total military exposures from Operation Castle; however, all of the non-military off-site exposures were attributed to Bravo.

Significant off-site human exposures occurred during three separate incidents. The first and highest exposures resulted when a Japanese fishing vessel, Daigo Fukuryu Maru (Fifth Lucky or Fortunate Dragon) with 23 crewmen aboard encountered fallout a few hours after the Bravo detonation. Unfortunately, the Japanese vessel was missed on preshot aerial sweeps and was about 83 nautical miles from ground zero when the detonation occurred. Although they were just outside the previously announced danger zone, the crew realized that they had observed a nuclear weapon test and began to secure their catch for immediate return to Japan. Visible particles began falling on the ship within a few hours. The trawler arrived at its home port of Yaizu, Japan on March 14. During the 13-day trip to Yaizu, the crewmen complained of discomfort, headache, burning eyes, nausea, and skin burns on exposed parts of their bodies. On reaching Yaizu, the men were hospitalized for treatment and observation and one man died 206 days after exposure (Conard et al. 1975; Lapp 1958). The extent to which radiation contributed to his death is uncertain. The estimated whole-body exposures for the Japanese crewmembers were 296 R (Conard, et al. 1982).

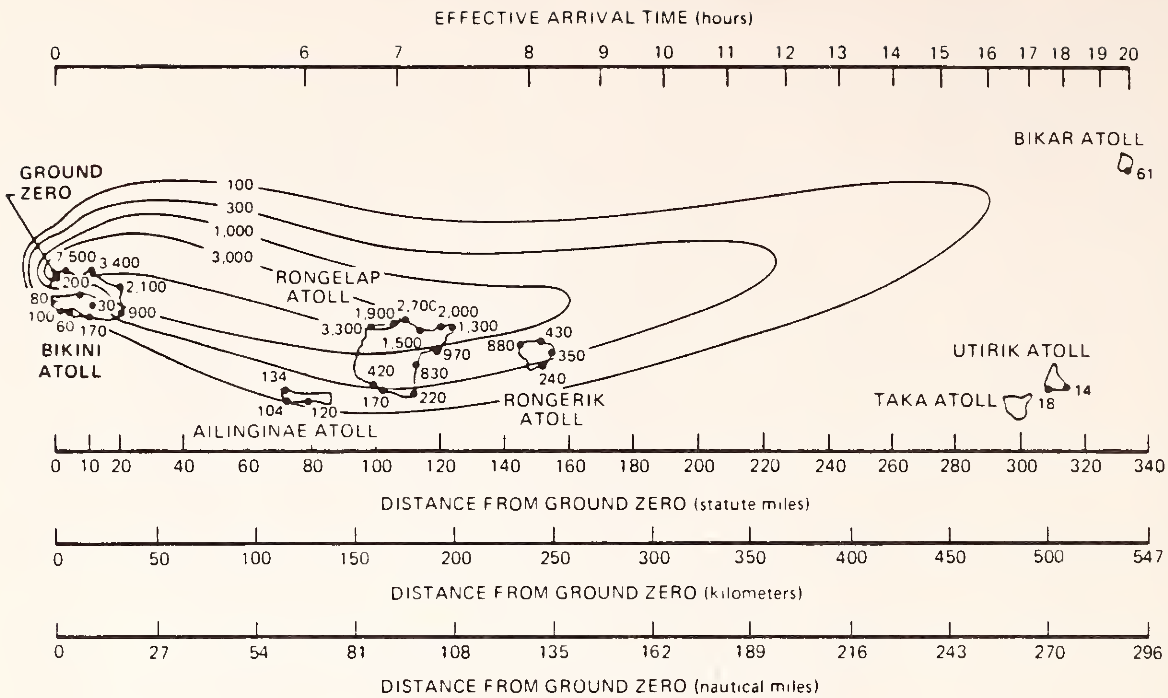



Figure V-9. Map showing estimated total cumulative dose contours in rad for CASTLE, BRAVO at H+96 hours and arrival times (Martin and Rowland 1982).

The government of the United States paid the Japanese Government 200 million dollars _ex gratia_ (Lapp 1958). _Ex Gratia_ payments are given for humanitarian or good will purposes and specifically exclude admissions of liability. About 150 million dollars were used to compensate the Japanese tuna fishing industry that was forced to condemn thousands of tons of radioactive contaminated tuna caught in waters subjected to fallout from Bravo and other tests in the Castle series. The 22 surviving Japanese fishermen from the Daigo Fukuryu Maru received an average payment of $5,000 each.

The next highest off-site human exposures occurred when radioactive fallout fell on the Marshall Islands just east of the Bikini Atoll. Sixty-four Marshallese on Rongelap Atoll received whole-body exposures of about 175 R. There were also 18 Rongelap people on a fishing expedition to nearby Ailinginae Atoll. They experienced a mean whole-body exposure estimated to be 69 R.

As part of the Air Force Weather Element for Operation Castle, a 28-man detachment was on Rongerik Atoll just southeast of Rongelap. The weather detachment consisted of 25 Air Force and 3 Army personnel. Based on film badge measurements and reconstructed exposures, these men received an average whole-body exposure of 78 R. Two other inhabited Atolls in the Marshall Islands also received significant fallout. Utirik Atoll's 157 residents were exposed to an estimated 14 R whole-body before evacuation and on Ailuk Atoll, 401 Marshall Islanders were estimated to have received 13 R whole-body exposure. The evacuation of personnel from Rongelap, Ailinginae, Rongerik, and Utirik is described by Martin and Rowland (1982). Marshallese on Ailuk Atoll were not evacuated because radiological survey data estimated that they would receive less than 20 R whole-body exposure if they remained on Ailuk.

Table V-6

Summary of Estimated Fallout Exposures from CASTLE-Bravo[a]

| Group | No. of People | Mean Gamma Exposure (R) |
|---|---|---|
| Joint Task Force 7 | | |
| Headquarters | 86 | 0.1 |
| Task Group 7.1 (Scientific) | | |
| Enewetak | 520 | 0.1 |
| Bikini | 485 | 0.5-2.4 |
| Task Group 7.2 (Army) | 1287 | 0.1 |
| Task Group 7.3 (Navy) | 5628 | 1.0 |
| Task Group 7.4 (Air Force) | 1725[b] | 0.1 |
| Task Group 7.5 (AEC) | | |
| Enewetak | 1220 | 0.1 |
| Bikini | 590 | 0.5 |
| Off-Site | | |
| Daigo Fukuryu Maru | 23 | 296 |
| Rongelap Marshall Islanders | 64 | 175 |
| Rongelap Islanders on Ailinginae | 18 | 69 |
| Utirik Marshall Islanders | 157 | 14 |
| Ailuk Marshall Islanders | 401 | 13 |
| U.S. Military Rongerik Detachment | 28 | 78 |
| USS Patapsco (AOG-1) | 110 | 3.3 |

[a]Compiled from Martin and Rowland 1982.

[b]Does not include aircraft sampler crews.

The last significant off-site exposures involved crewmen of the USS Patapsco. The Patapsco, a gasoline tanker, had been at Enewetak 2 days prior to the Bravo detonation. Because the Patapsco was not equipped with decontamination washdown systems, it had been ordered to return to Pearl Harbor at full speed. However, a cracked cylinder liner slowed the vessel to about one-third full speed and it was only about 180 to 195 nautical miles east of Bikini when the Bravo detonation occurred. By mid-afternoon of the next day, at a range of 565 to 586 nautical miles from ground zero, the Patapsco began to receive fallout, but the exposure intensity is not accurately known. No decontamination was attempted by the Patapsco crew since the fallout was considered harmless and the vessel did not have radiation detection devices on board. Based on radiation measurements made when the Patapsco arrived at Pearl Harbor, the calculated exposure range was 0.18 to 0.62 R/hr. Although highly uncertain, one exposure assignment is 18 R of whole-body radiation (Grissom et al. 1983). The same source lists 113 crewmen on the Patapsco whereas the official United States Navy records assign a 3.3 R whole-body exposure for 110 men on board (Martin and Rowland 1982). This estimate is based on recent analyses that considered the natural washdown provided by documented rain and the effects of weather deck exposures versus below deck exposures.

The first information that Joint Task Force 7 headquarters received, indicating high level fallout off-site, was a radio message from the Task Group Weather Element on Rongerik. The Rongerik detachment had a recording ratemeter with a full scale of 0.1 R/hr. It was off-scale since 1515 on March 1. On March 2, an aerial survey of Rongerik and other atolls indicated that

evacuation was necessary. Accordingly, destroyers and amphibious aircraft evacuated all personnel from Rongelap, Ailinginae, Rongerik, and Utirik. The people were decontaminated in-route to the naval base on Kwajalein Atoll where extensive medical examinations were conducted.

The highest recorded exposure to United States personnel from Bravo was 96 R. Three Navy men assigned to the Bikini lagoon boat pool turned in film badges that indicated from 85-96 R whole-body exposure. These film badges were not processed until 10 days after Bravo and it is unclear how these men could have received such an exposure, based on their duty assignments and documented exposures to men with similar assignments. Subsequent medical followup did not indicate that an exposure of such magnitude had occurred and implied a discrepancy in badging or wearing of badges. For all of the Joint Task Force 7 personnel, including 10,110 people, 524 received exposures greater than 3.9 R.

Radiation Exposures to the Marshallese

In the two days between the Bravo shot and evacuation by the United States Navy, people living on Rongelap reported symptoms relating to irritation of their skin and gastrointestinal tracts. The same symptoms were noted to a lesser extent by people on Ailinginae, but no complaints were expressed by people on Utirik. The severity of the symptoms were correlated with the amount of fallout and radiation dose. A quarter of the people on Rongelap complained of itching and burning with some eye irritation. These early symptoms were thought to be related to beta burns, but the caustic nature of the fallout particles may have been a contributory factor. Gastrointestinal symptoms in the people on Rongelap consisted of anorexia and nausea (~ 67%), and to a lesser extent vomiting (~ 10%).

One of the earliest medical findings was a lowering of leukocyte and platelet levels in circulating blood (Conard et al. 1975). Even in the 157 people on Utirik who received an estimated 14 R, it was possible to distinguish a slight platelet depression. Beta burns are also described in detail in the original report of medical findings (Cronkite et al. 1956). Evidence of beta burns appeared 12 to 14 days after exposure for the people on Rongelap and later at decreased intensity for the Marshallese on Ailinginae. Americans on Rongerik had beta burns on about 40% of the men, whereas on Rongelap and Ailinginae about 90% experienced beta burns. No beta burns were seen on Marshallese living on Utirik. Most of the beta burns healed within a few months of the radiation exposure.

Monitoring of Marshallese for potential thyroid abnormalities was an important part of the follow up medical program from the beginning. Initially, it was not considered likely that their thyroids had received a sufficient dose of radioactive iodine to result in abnormalities. In retrospect this proved wrong, since injury to the thyroid and its sequela are the most serious late effects of the fallout exposures to Marshallese that have been seen to date.

Beginning several years after exposure in 5 of 19 Marshallese children exposed at less than 10 years of age, growth retardation was noted. As techniques improved for more accurate determinations of protein-bound iodine, it became apparent that thyroid function had been impaired and that the growth retardation was the result of primary thyroid damage rather than pituitary damage. Supplementary thyroxine treatments reversed the growth retardation.

At nine years after exposure, a 12-year-old girl was diagnosed as having an asymptomatic thyroid nodule and this finding has been repeated in other subjects. Two of three Rongelap children exposed in utero developed thyroid nodules by 1981. Of the 67 exposed Rongelap people, (3 exposed in utero) about 75% of those under 10 years of age at the time of exposure developed nodules. For individuals over 18 years old only about 10% developed nodules. Of the total 250 Marshallese (includes in utero exposures), 45 have had thyroid surgery. Early estimates of thyroid doses were not consistent with the high frequency of thyroid nodules observed. Table V-7 is adapted from Conard et al. (1980) and shows the calculated thyroid doses to the Marshallese

Table V-7

Estimated Radiation Doses to Fallout-Exposed Marshallese[a]

| Atoll | Number[b] | Estimated Whole-body Gamma Dose (rem) | Estimated Thyroid Dose (rem) by Age at Exposure: < 10 yr | 10-18 yr | > 18 yr |
|---|---|---|---|---|---|
| Rongelap | 67 | 175 | 810-1800 | 334-810 | 335 |
| Ailinginae | 19 | 69 | 275-450 | 190 | 135 |
| Utirik | 163 | 14 | 60-95 | 30-60 | 30 |

[a]Adapted from Conard *et al*. 1980.

[b]Includes *in utero* exposures (3 on Rongelap, 1 on Ailinginae, and 6 on Utirik).

that had been generally accepted, but because these estimated doses were not consistant with the frequent development of thyroid nodules and neoplasias, a comprehensive effort was begun to recalculate the potential dose to the thyroid. Four new approaches have been used to recalculate these doses (Lessard *et al*. 1983). They include (1) relating radiochemical analyses of pooled urine samples during March 1954 to current intake, retention, and excretion models to determine $^{131}I$ inhaled and ingested, (2) estimating airborne concentrations and land surface contamination from radioiodine using neutron activation studies on archival soil samples, (3) estimating airborne concentrations and land surface contamination by radioiodine derived from the source term, weather data, and current computer models that predict atmospheric diffusion and fallout deposition, and (4) determining fallout components based on Bikini ash, the radioactive fallout which fell on the Japanese fishing trawler Daigo Fukuryu Maru just off Rongelap on March 1, 1954. Table V-8 summarizes the revised thyroid dose estimates. The newer dose estimates are about 4 times higher than previous thyroid dose estimates and are more consistent with the observed health effects.

Table V-8

Total Thyroid Absorbed Dose Estimates for the Marshallese Exposed in 1954 to Bravo Fallout (rad)[a]

| | Rongelap | | Ailinginae | | Utirik | |
|---|---|---|---|---|---|---|
| Age | Probable | Maximum | Probable | Maximum | Probable | Maximum |
| Adult Male | 1200 | 4200 | 400 | 1200 | 160 | 610 |
| Adult Female | 1300 | 4600 | 410 | 1300 | 170 | 650 |
| 14 | 1600 | 5800 | 530 | 1700 | 230 | 890 |
| 12 | 1800 | 6600 | 570 | 1900 | 250 | 970 |
| 9 | 2200 | 8200 | 660 | 2300 | 310 | 1200 |
| 6 | 2600 | 9800 | 760 | 2700 | 350 | 1400 |
| 1 | 5200 | 20000 | 1400 | 5300 | 680 | 2700 |
| Newborn | 450 | 1200 | - | - | 60 | 200 |
| *in utero*, 3rd tri. | 880 | 2900 | - | - | 110 | 400 |
| *in utero*, 2nd tri. | - | - | 610 | 2100 | 270 | 1000 |

[a]Adapted from Lessard *et al*. 1983.

The other five detonations of Operation Castle did not result in significant personnel radiation exposures. To enable completion of tests after Bravo, it was necessary to issue several waiver authorizations permitting individuals to receive exposures as high as 7.8 R. Even this level was exceeded for a limited number of cases. For the more than 10,000 personnel participating in Operation Castle, 319 received whole-body exposures over 5 R.

Test series after Operation Castle resulted in lower personnel radiation exposures (Table V-5). Operation Wigwam in 1955 included one shot, a 30 kiloton underwater detonation off the coast of Southern California, that resulted in an average exposure to the 6,549 participants of 8 mR. Only one exposure was reported to be over 1 R. Operation Redwing in 1956 was a 17-shot series conducted on Enewetak (11 shots) and Bikini (6 shots) that resulted in an average exposure of 0.8 R with 19 people being exposed to over 5 R. Operation Hardtack I was a 35-shot series that occurred just prior to the nuclear weapon test moratorium in 1958. Bikini Atoll was the site for 10 tests, 22 were conducted on Enewetak, 2 were conducted near Johnston Island, and 1 at another site in the Pacific. Exposures to naval personnel averaged 0.57 R with only 2 people receiving an exposure over 5 R. Operation Hardtack I was the last test series conducted at the Pacific Proving Grounds.

Operation Argus was a highly secret test series conducted in the South Atlantic. The three tests were launched by rockets. Detonations of 1 to 2 kiloton yields at 300 mile altitudes were designed to test nuclear weapon effects on communications. No one of the 4,456 members of Task Force 88 received a significant radiation exposure over background. The United States Navy conducted Operation Argus through Task Force 88.

In 1962, after the Soviet Union resumed nuclear weapon testing, the United States conducted Operation Dominic I in the Pacific. This included 36 shots with 24 in the Christmas Island area, 10 in the Johnston Island area, and 2 tests detonated in open ocean areas. Operation Dominic I resulted in an average exposure of 90 mr to 15,932 Navy participants. One person was exposed to more than 5 R. Operation Dominic I was the last series of nuclear weapon tests to be conducted in the atmosphere. Since 1962, all nuclear weapon tests conducted by the United States have been underground shots. Most of these tests have been conducted at the Nevada Test Site, but some tests were also conducted at the Nellis Air Force Base Bombing Range in Nevada; in central and northwestern Nevada; Rifle, Colorado; Farmington, New Mexico; Hattiesburg, Mississippi; and on Amchitka Island in the Aleutions of the coast of Alaska. For all atmospheric tests conducted by the United States, including the tests in the continental United States, a total of 1,319 out of about 232,000 participants were exposed to more than 5 R. Of the 1,319 exposures over 5 R, 319 were associated with Operation Castle.

## Cleanup of the Bikini and Enewetak Atolls

In 1966, people originally from the Bikini Atoll, living since the late 1940s on Kili Island, petitioned President Johnson to return to their homeland. Beginning in 1967, numerous radiological surveys of both Bikini and Enewetak Atolls were conducted. In 1968, an *ad hoc* committee reviewed the survey results for Bikini Atoll and decided that Bikini and Eneu Islands were safe for habitation with certain restrictions designed to reduce radiation exposures. Also in 1968, President Johnson announced that the people of Bikini could return to their atoll after the United States Government had cleaned up the islands and planted several thousand food-bearing trees. By 1969, about 30 people were living on Eneu Island and by 1971, about 50 people were on Bikini Island (Conard *et al*. 1975). From 1971 to 1978, several more families moved back and settled on Bikini and Eneu Islands. In the first few years after their return to Bikini Atoll, people ate a diet that consisted almost exclusively of imported food. Whole-body measurements of radioactivity in Bikini Atoll residents were performed in 1974, 1977, and 1978. By 1977, the fruit-bearing trees began to mature and their fruits were incorporated into the diet, causing the

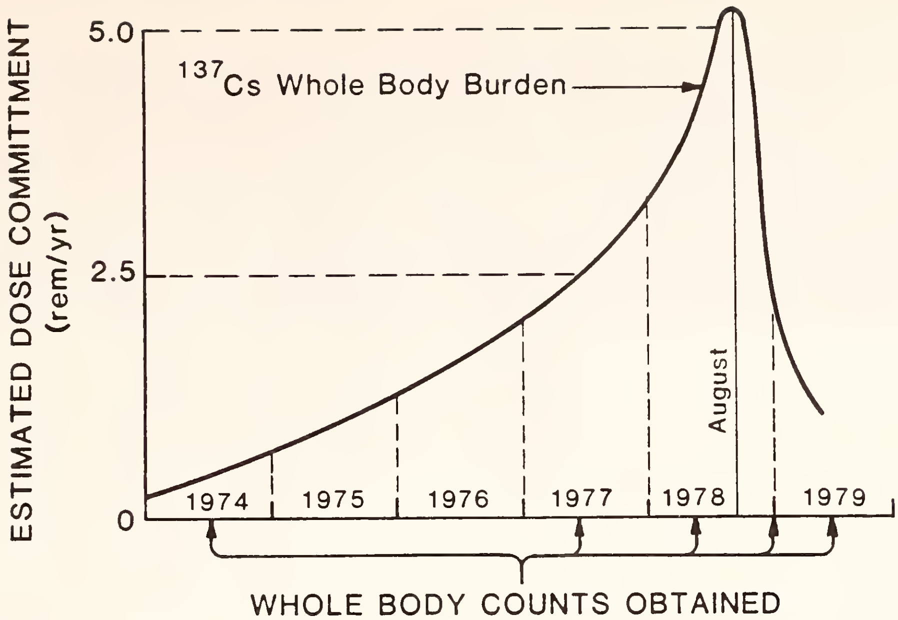



Figure V-10. Measured whole body burdens of $^{137}$Cs in Bikini Atoll residents (modified from Bair *et al.* 1980).

levels of $^{137}$Cs in people to be significantly greater than expected. The United States' representatives advised the Marshallese people on Bikini not to eat the fruits of plants on Bikini Island; however, the people continued to eat the fruits, especially during times of famine or when outside food was late or insufficient. By 1978, it was clear that their $^{137}$Cs body burdens were above recommended standards (Bair et al. 1980). Consequently, the Marshallese living on Bikini Atoll were again requested to leave their homes by the United States Government and a booklet was prepared in both Marshallese and English explaining why the people were evacuated (Bair et al. 1980). Whole-body counts of the Marshallese were taken in 1979 and 1980 after evacuation from Bikini. The buildup and reduction of their $^{137}$Cs body burdens is shown in Figure V-10. At this time, it is not clear when they will be able to return to their homeland.

In April 1972, the High Commissioner of the Trust Territory of the Pacific Islands, Edward E. Johnston, announced that the United States was preparing to return Enewetak Atoll to its former inhabitants (Friesen 1982). The people had been living on Ujelang Atoll since 1948. In May 1972, six elected leaders were allowed to visit the Atoll. The Marshallese "were deeply gratified to be able to visit their ancestral homeland but were mortified by what they saw" (Friesen 1982). The Atoll had been used for cratering experiments using conventional high explosives. The Enewetak people were unhappy and obtained a court order halting the program in October 1972. By November 1972, the United States Government was committed to a program for rehabilitation of Enewetak Atoll which Congress authorized in 1976.

A series of engineering, feasibility, and radiological surveys were conducted to define the problem. A 2,200 page report entitled, Enewetak Radiological Survey (NVO-140 1973) was published in October 1973. Finally, an Atomic Energy Commission Task Group reviewed the results of NVO-140

and information on life-style, diet, and the rehabilitation preferences of the Enewetak people to develop a cleanup plan for Enewetak. The objective for cleanup at Enewetak was stated by the Task Group in the following passage:

> "For contaminated soil, other than plutonium, the Task Group has not included removal of such soil in its recommendations and therefore there would be no requirement to select a method of disposal. If such disposal were required, the objective would be to assure that there would be no pathway for any exposure of the Enewetak people to this radioactivity and a minimal follow-up requirement to insure that this situation continues after disposal.
>
> "The Task Group view is that because of its extremely long half-life, disposal of plutonium in the form of contaminated soil and scrap is a problem of greater magnitude than for fission products and induced activity. In its deliberations, the Task Group has assumed that the deposition of such material will be such that there is no potential for exposure of the residents of the Atoll once cleanup has been completed. This is then the objective for cleanup."

The actual cleanup began in earnest in 1977 under the Energy Research and Development Administration which assumed many of the functions of the Atomic Energy Commission. The Department of Energy later assumed the functions of the Energy Research and Development Administration. The Department of Energy and its predecessors were advisors to the Defense Nuclear Agency during both planning and execution of the cleanup of Enewetak Atoll. Over 89,000 cubic meters of the surface soil were removed from five islands and placed in a crater that was formed during the testing period along with other contaminated debris. Some subsurface soil was also removed from several locations where radiological measurements indicated the presence of radioactivity above the action criteria (Friesen 1982). Tables V-9, V-10, and V-11 show the lack of long-term effectiveness of the cleanup on reducing the concentration of $^{137}$Cs, $^{90}$Sr, and $^{239,240}$Pu in soil.

Some Marshallese returned to the Enewetak Atoll in 1980 to live on the southern islands. Several hypothetical living patterns were developed to estimate their potential radiation doses (Bair et al. 1979). Because the northern islands were the most heavily contaminated, the recommended living patterns were restricted to the southern islands and food collection from the more heavily contaminated islands in the northern and northeastern sector was discouraged. Island Yvonne (Runit) was quarantined because it was one of the most heavily contaminated islands.

Of special significance is the radioactive contamination remaining on Island Janet (Enjebi). Island Janet is one of the largest areas of land (about 120 hectares) comprising Enewetak Atoll and it still has a relatively high level of radioactive contamination in the soil. One of the projected living patterns assumes that the Marshallese will live on the islands of Enewetak, David (Japtan), and Elmer, sometimes called Parry (Medren). However, it is resonable to assume that Island Janet, one of the largest islands in fairly close proximity to the dwelling islands, would eventually provide much of the natural foods. Table V-12 provides a comparison of soil contamination levels for the principal dwelling islands in Bikini and Enewetak Atolls including Janet (Enjebi). Normalizing all of the soil contamination levels to the average amount on the three principal dwelling islands of Enewetak Atoll indicates that Janet (Enjebi) is about 2 to 3 times more contaminated than Nan (Eneu) in Bikini Atoll and Bikini Island is 2 to 3 times more contaminated than Janet.

If the Marshallese were not able to live on Bikini and Eneu without accumulating excessive body burdens of $^{137}$Cs and $^{90}$Sr (Bair et al. 1980), reoccupation of Enewetak may result in a similar situation. Poor success was achieved in convincing some Bikini inhabitants to refrain from eating native foods from the contaminated islands. Coconut products are a significant portion of the Marshallese diet that probably was underestimated. On Bikini and Enewetak Atolls, people reoccupied the islands shortly after the coconut trees were planted. However, no

Table V-9

Results by Island for $^{137}Cs$ in 0-15 cm Soil Samples from the 1972 Radiological Survey and the 1979 Fission Product Data Base Program (Friesen 1982)

| | Pre-Cleanup 1972 Radiological Survey | | | Post-Cleanup 1979 Fission Product Data Base Program | | |
|---|---|---|---|---|---|---|
| Island | No. of Locations Sampled | Range of Activity, all Depths (pCi/g) | 0-15 cm Mean (pCi/g) | No. of Locations Sampled | Range of Activity, all Depths (pCi/g) | 0-15 cm Mean (pCi/g) |
| Alice | 23 | 0.7 - 141 | 44.1 | 26 | < 0.4 - 114 | 39.9 |
| Belle | 36 | 0.4 - 170 | 47.5 | 40 | < 0.4 - 204 | 61.0 |
| Clara | 13 | 0.8 - 110 | 35.4 | 8 | 0.3 - 105 | 22.4 |
| Daisy | 20 | 0.9 - 33 | 10.5 | 26 | < 0.4 - 34 | 6.8 |
| Edna | 8 | 2.7 - 6.4 | 4.7 | 5 | < 0.4 - 7 | 2.9 |
| Irene | 58 | 0.2 - 41 | 7.3 | 53 | < 0.4 - 54 | 6.1 |
| Janet | 139 | 0.6 - 180 | 27.0 | 364 | < 0.4 - 142 | 16.4 |
| Kate | 26 | 0.1 - 37 | 13.1 | 18 | < 0.4 - 35 | 7.8 |
| Lucy | 28 | 0.1 - 25 | 10.3 | 22 | < - 40 | 11.7 |
| Percy | 6 | 0.1 - 17 | 7.3 | 2 | < 0.4 - 2 | 0.6 |
| Mary | 22 | 0.03 - 26 | 8.4 | 12 | < 0.4 - 18 | 6.0 |
| Mary's Daughter | a | a | a | 3 | < 0.4 - 72 | 12.3 |
| Nancy | 25 | 0.01 - 28 | 11.6 | 11 | < 0.4 - 60 | 10.8 |
| Olive | 26 | 0.1 - 28 | 7.7 | 50 | < 0.4 - 60 | 7.5 |
| Pearl | 53 | 0.2 - 55 | 12.4 | 72 | < 0.4 - 43 | 7.2 |
| Pearl's Daughter | a | a | a | 2 | < 0.4 - 7 | 5.6 |
| Ruby | 5 | 0.7 - 7.2 | 3.2 | 3 | 1.1 - 11 | 2.0 |
| Sally | 27 | 0.1 - 30 | 5.7 | 137 | < 0.4 - 43 | 3.5 |
| Sally's Child | 6 | 0.03 - 29 | 8.9 | 4 | < 0.4 - 13 | 6.9 |
| Tilda | 32 | 0.04 - 20 | 4.2 | 48 | < 0.4 - 20 | 3.2 |
| Ursula | 31 | 0.1 - 7.8 | 2.6 | 15 | < 0.4 - 4 | 1.2 |
| Vera | 25 | 0.03 - 12 | 4.4 | 48 | < 0.4 - 20 | 3.0 |
| Wilma | 23 | 3.0 - 7.2 | 2.0 | 17 | < 0.4 - 5 | 1.3 |
| Yvonne[c] | 51 | 0.02 - 3.6 | 1.0 | 14 | < 0.4 - 11 | 1.5 |
| Sam | 5 | 0.02 - 0.5 | 0.38 | b | b | b |
| Tom | 5 | 0.07 - 0.56 | 0.32 | b | b | b |
| Uriah | 8 | 0.02 - 0.23 | 0.11 | b | b | b |
| Van | 6 | 0.05 - 0.20 | 0.14 | b | b | b |
| Alvin | 5 | 0.03 - 0.29 | 0.11 | b | b | b |
| Bruce | 13 | 0.02 - 1.1 | 0.40 | b | b | b |
| Clyde | 4 | 0.02 - 0.13 | 0.06 | b | b | b |
| David | 48 | 0.03 - 1.0 | 0.40 | b | b | b |
| Rex | 7 | 0.02 - 1.2 | 0.51 | b | b | b |
| Elmer | 51 | 0.02 - 1.2 | 0.32 | b | b | b |
| Walt | 5 | 0.04 - 0.3 | 0.15 | b | b | b |
| Fred | 24 | 0.02 - 0.48 | 0.25 | b | b | b |
| Glenn | 28 | 0.01 - 1.8 | 0.60 | b | b | b |
| Henry | 15 | 0.004 - 0.7 | 0.25 | b | b | b |
| Irwin | 8 | 0.008 - 0.47 | 0.13 | b | b | b |
| James | 8 | 0.02 - 0.22 | 0.08 | b | b | b |
| Keith | 13 | 0.01 - 0.81 | 0.28 | b | b | b |
| Leroy | 11 | 0.5 - 10 | 5.06 | 8 | < 0.4 - 28 | 4.2 |

[a]Not sampled in 1972 survey.

[b]Not sampled in 1979 FPDB survey.

[c]South of 1310 bunker.

Table V-10

Results by Island for $^{90}Sr$ in 0-15 cm Soil Samples from the 1972 Radiological Survey and the 1979 Fission Product Data Base Program (Friesen 1982)

| | Pre-Cleanup | | | Post-Cleanup | | |
|---|---|---|---|---|---|---|
| | 1972 Radiological Survey | | | 1979 Fission Product Data Base Program | | |
| Island | No. of Locations Sampled | Range of Activity, all Depths (pCi/g) | 0-15 cm Mean (pCi/g) | No. of Locations Sampled | Range of Activity, all Depths (pCi/g) | 0-15 cm Mean (pCi/g) |
| Alice | 23 | 14 - 430 | 107.9 | 7 | 1.3 - 347 | 85.9 |
| Belle | 36 | 9.8 - 670 | 148.9 | 11 | 3.5 - 339 | 107.4 |
| Clara | 13 | 13 - 310 | 99.2 | 4 | 1.4 - 243 | 42.8 |
| Daisy | 20 | 3.4 - 380 | 107.7 | 8 | 1.9 - 144 | 34.8 |
| Edna | 8 | 30 - 220 | 68.6 | 3 | 4.3 - 48 | 21.7 |
| Irene | 56 | 8.4 - 570 | 52.8 | 15 | 0.6 - 136 | 31.0 |
| Janet | 140 | 1.6 - 630 | 72.9 | 99 | < 0.1 - 244 | 31.9 |
| Kate | 26 | 1.6 - 200 | 43.5 | 6 | 1.0 - 31 | 13.3 |
| Lucy | 28 | 4.4 - 83 | 30.1 | 8 | 1.0 - 94 | 21.9 |
| Percy | 6 | 3.6 - 73 | 34.6 | 2 | 2.0 - 7 | 5.4 |
| Mary | 22 | 1.2 - 140 | 34.8 | 4 | 1.1 - 46 | 14.2 |
| Mary's Daughter | a | a | a | 1 | 5.2 - 107 | 41.9 |
| Nancy | 25 | 3.6 - 110 | 39.3 | 6 | < 0.15 - 82 | 20.1 |
| Olive | 26 | 2.0 - 70 | 21.5 | 12 | < 0.12 - 83 | 16.2 |
| Pearl | 52 | 2.3 - 140 | 28.3 | 17 | 0.4 - 38 | 11.4 |
| Pearl's Daughter | a | a | a | 1 | 1.3 - 28 | 18.0 |
| Ruby | 5 | 7.1 - 63 | 24.3 | 1 | 5.5 - 9 | 5.8 |
| Sally | 27 | 0.9 - 140 | 16.0 | 39 | < 0.10 - 25 | 4.4 |
| Sally's Child | 6 | 3.0 - 89 | 25.0 | 4 | 1.0 - 60 | 16.7 |
| Tilda | 32 | 2.2 - 54 | 19.1 | 15 | < 0.12 - 25 | 5.6 |
| Ursula | 31 | 0.9 - 19 | 8.2 | 15 | < 0.08 - 70 | 3.0 |
| Vera | 25 | 1.1 - 68 | 12.5 | 13 | 0.2 - 29 | 4.8 |
| Wilma | 23 | 0.3 - 19 | 6.0 | 5 | 0.2 - 19 | 2.9 |
| Yvonne[c] | 47 | 0.1 - 20 | 3.3 | 5 | < 0.13 - 5 | 1.1 |
| Sam | 5 | 0.5 - 0.8 | 0.72 | b | b | b |
| Tom | 5 | 0.18 - 1.2 | 0.72 | b | b | b |
| Uriah | 8 | 0.05 - 1.0 | 0.45 | b | b | b |
| Van | 6 | 0.10 - 0.81 | 0.41 | b | b | b |
| Alvin | 5 | 0.21 - 0.74 | 0.44 | b | b | b |
| Bruce | 13 | 0.03 - 1.8 | 0.59 | b | b | b |
| Clyde | 3 | 0.12 - 0.36 | 0.23 | b | b | b |
| David | 47 | 0.08 - 2.6 | 0.55 | b | b | b |
| Rex | 6 | 0.03 - 1.6 | 0.51 | b | b | b |
| Elmer | 51 | 0.02 - 5.1 | 0.76 | b | b | b |
| Walt | 5 | 0.25 - 0.6 | 0.41 | b | b | b |
| Fred | 24 | 0.16 - 1.5 | 0.61 | b | b | b |
| Glenn | 28 | 0.09 - 3.9 | 1.37 | b | b | b |
| Henry | 14 | 0.13 - 2.2 | 0.75 | b | b | b |
| Irwin | 8 | 0.14 - 1.6 | 0.69 | b | b | b |
| James | 8 | 0.13 - 2.2 | 0.69 | b | b | b |
| Keith | 13 | 0.03 - 1.8 | 0.88 | b | b | b |
| Leroy | 11 | 0.42 34 | 16.8 | 8 | 0.15 - 20 | 5.1 |

[a]Not sampled in 1972 survey.

[b]Not sampled in 1979 FPDB survey.

[c]South of 1310 bunker.

Table V-11

Results by Island for $^{239,240}Pu$ in 0-15 cm Soil Samples from the 1972 Radiological Survey and the 1979 Fission Product Data Base Program (Friesen 1982)

| | Pre-Cleanup 1972 Radiological Survey | | | Post-Cleanup 1979 Fission Product Data Base Program | | |
|---|---|---|---|---|---|---|
| Island | No. of Locations Sampled | Range of Activity, all Depths (pCi/g) | 0-15 cm Mean (pCi/g) | No. of Locations Sampled | Range of Activity, all Depths (pCi/g) | 0-15 cm Mean (pCi/g) |
| Alice | 22 | 3.9 - 68 | 15.6 | 26 | < 2 - 226 | 20.5 |
| Belle | 35 | | | | | |
| Clara | 13 | 3.5 - 88 | 31.6 | 8 | < 2 - 245 | 34.5 |
| Daisy | 20 | 3.8 - 98 | 31.6 | 26 | < 2 - 121 | 25.4 |
| Edna | 8 | 13 - 24 | 19.4 | 5 | 9.4 - 28 | 17.8 |
| Irene | 56 | 2.4 - 280 | 26.2 | 53 | < 4 - 187 | 29.5 |
| Janet | 138 | 0.1 - 175[d] | 16.2 | 364 | < 3 - 119 | 10.1 |
| Kate | 26 | 0.2 - 50 | 11.3 | 18 | < 1.5 - 27 | 5.0 |
| Lucy | 28 | 1.5 - 23 | 7.7 | 22 | < 1.5 - 74 | 10.1 |
| Percy | 6 | 1.5 - 23 | 9.0 | 2 | < 1.5 - 2.7 | 1.7 |
| Mary | 22 | 0.9 - 35 | 10.1 | 12 | < 1.5 - 27 | 7.2 |
| Mary's Daughter | a | a | a | 3 | < 1.5 - 44 | 8.4 |
| Nancy | 25 | 1.3 - 28 | 10.1 | 14 | < 1.5 - 48 | 8.0 |
| Olive | 26 | 1.9 - 30 | 8.4 | 50 | < 2 - 72 | 6.4 |
| Pearl | 52 | 0.3 - 530 | 38.3 | 72 | < 3.5 - 130 | 15.5 |
| Pearl's Daughter | a | a | a | 2 | < 6 - 85 | 44.8 |
| Ruby | 5 | 3.0 - 24 | 14.5 | 3 | < 3.5 - 7.5 | 5.6 |
| Sally | 27 | 0.2 - 130 | 11.0 | 137 | < 2 - 72 | 2.2 |
| Sally's Child | 6 | 5.6 - 78 | 26.9 | 4 | < 1.5 - 51 | 12.1 |
| Tilda | 29 | 1.1 - 34 | 6.5 | 48 | < 1.5 - 20 | 2.0 |
| Ursula | 31 | 0.2 - 4.2 | 1.8 | 15 | < 1.5 - 2.5 | 0.6 |
| Vera | 25 | 0.6 - 25 | 4.3 | 48 | < 1.5 - 22 | 2.2 |
| Wilma | 22 | 0.1 - 5.3 | 1.8 | 17 | < 1.5 - 10 | 1.1 |
| Yvonne[c] | 49 | 0.02 - 50 | 8.7 | 14 | < 4.5 - 93 | 11.6 |
| Sam | 5 | 0.03 - 0.2 | 0.09 | b | b | b |
| Tom | 5 | 0.01 - 0.13 | 0.08 | b | b | b |
| Uriah | 8 | 0.02 - 0.12 | 0.09 | b | b | b |
| Van | 6 | 0.04 - 0.11 | 0.08 | b | b | b |
| Alvin | 5 | 0.02 - 0.11 | 0.06 | b | b | b |
| Bruce | 13 | 0.02 - 0.22 | 0.09 | b | b | b |
| Clyde | 4 | 0.04 - 0.11 | 0.06 | b | b | b |
| David | 48 | 0.004 - 0.23 | 0.05 | b | b | b |
| Rex | 7 | 0.02 - 0.06 | 0.04 | b | b | b |
| Elmer | 50 | 0.01 - 5.5 | 0.21 | b | b | b |
| Walt | 5 | 0.02 - 0.06 | 0.04 | b | b | b |
| Fred | 23 | 0.02 - 0.4 | 0.08 | b | b | b |
| Glenn | 28 | 0.005 - 0.3 | 0.11 | b | b | b |
| Henry | 14 | 0.07 - 0.23 | 0.14 | b | b | b |
| Irwin | 8 | 0.01 - 0.22 | 0.13 | b | b | b |
| James | 8 | 0.02 - 0.16 | 0.08 | b | b | b |
| Keith | 13 | 0.01 - 0.17 | 0.11 | b | b | b |
| Leroy | 11 | 0.02 - 2.3 | 1.15 | 8 | < 3 - 24 | 1.7 |

$^{239,240}Pu$ estimated from $^{241}Am$ data.

[a]Not sampled in 1972 survey.

[b]Not sampled in 1979 FPDB survey.

[c]South of 1310 bunker.

[d]This value is suspect in light of other information. The next highest activity was 116 pCi/g, which appears to be a reliable value.

Table V-12

Ratios of Radioactive Contamination ($^{137}Cs$, $^{90}Sr$, $^{239}Pu$, $^{241}Am$) in Soil on Islands of Enewetak and Bikini Atolls (Bair *et al*. 1980)

| Atoll | Island | Ratio |
|---|---|---|
| Enewetak | Enewetak (Fred)<br>Japtan (David)<br>Medren (Elmer or Parry) | 1 |
| Bikini | Eneu (Nan) | 30 |
| Enewetak | Enjebi (Janet) | 60-90 |
| Bikini | Bikini (How) | 180-270 |

significant whole-body accumulation of $^{137}Cs$ and $^{90}Sr$ occurred until the coconut trees had matured. Thus, it appears that if coconuts are available, some Marshallese may use the coconuts and coconut products without serious regard as to the radioactive contamination. Better success was achieved with people on Rongelap Atoll who generally observed the food gathering restrictions.

Personal Injury Claims Resulting from Oceanic Nuclear Weapons Tests

To date, 483 claims have been filed with the Veterans Administration by former Naval personnel nuclear weapon test participants who claimed injuries caused by radiation exposure (Grissom *et al*. 1983). By September 1983, 18 lawsuits had been filed solely as a result of Operation Crossroads. Several lawsuits have also been filed against National Laboratories and other government-related organizations (Table V-13). One class action lawsuit was filed by Runnels *et al*. in the U. S. District Court in Hawaii that seeks 2.75 billion dollars in compensation for injuries alledgedly received during Operation Wigwam.

The most significant lawsuits filed to date are related to fallout from shot Bravo. Two lawsuits, Antolok *et al*. and Alee *et al*., are each seeking 4 billion dollars for loss of land, radiation exposures, and punitive damages for the Marshallese plantiffs. A related lawsuit, Curbow *et al*., is seeking 10 million dollars on behalf of five of the 28 American servicemen subjected to Bravo fallout on Rongerik Atoll in 1954. None of these lawsuits has reached trial. One important and unresolved question is, who among the defendants could be liable under the Federal Tort Claims Act? Since the United States may be immune to claims under the Federal Tort Claims Act and since the National Laboratories were probably acting under authority from the President of the United States, it remains to be seen whether any of the defendants can be held liable for injuries due to the nuclear weapon testing program.

Marshall Islands Plebiscite

On September 7, 1983, citizens of the Marshall Islands voted on a proposal to establish a Compact of Free Association with the United States. About 58% of the voters approved the Compact which would give complete independence to the 33,000 inhabitants of the 24 Atolls in the Marshall Islands, except in defense matters. The results of the plebiscite have been ratified by the legislature of the Marshallese Government and the Congress of the United States.

Section 177 of the Compact of Free Association deals with all legal claims relating to the nuclear weapons testing program. Under the terms of Section 177, a fund of $150,000,000 is to be set up and invested in securities in the United States to provide income for the Marshallese involved in the 1954 Bravo incident. The legality of the terms of Section 177 may be questioned;

Table V-13. Summary of Lawsuits from Nuclear Weapons Used in Combat and Oceanic Tests[a]

| Case | | Plaintiffs | Defendants USA | UC[b] | SNL[c] | Others | Operation Name | Year | Venue |
|---|---|---|---|---|---|---|---|---|---|
| Molsbergen | 1 | Survivor of Serviceman | X | X | | | Nagasaki, Japan (Combat) | 1945 | USDC N.D. Cal. |
| Solano | 1 | Survivor of Serviceman | X | X | | | Hiroshima, Japan (Combat) | 1945 | USDC N.D. Cal. |
| Juda | 990 | People of Bikini | X | | | | All | 1946-1958 | Court of Claims |
| Nitol | 190 | People of Marshall Islands | X | | | | All | 1946-1958 | Court of Claims |
| Peters | 293 | People of Enewetak | X | | | | All | 1946-1958 | Court of Claims |
| Beaman | 2 | Serviceman and Son | X | X | | | Crossroads | 1946 | USDC N.D. Cal. |
| Benson | 1 | Survivor of Serviceman | X | X | | | Crossroads | 1946 | USDC N.D. Cal. |
| Capua | 5 | Survivors of Serviceman | X | X | | X | Crossroads | 1946 | USDC D. N.J. |
| Carsillo | 4 | Survivors of Serviceman | X | X | | | Crossroads | 1946 | USDC N.D. Cal. |
| Collins | 1 | Survivor of Serviceman | | X | X | X | Crossroads | 1946 | USDC N.D. Cal. |
| Cordray | 2 | Serviceman and Son | X | X | | | Crossroads | 1946 | USDC N.D. Cal. |
| Demuth | 1 | Survivor of Serviceman | | X | X | X | Crossroads | 1946 | USDC N.D. Cal. |
| Erspamer | 9 | Survivors of Serviceman | | X | | | Crossroads | 1946 | Cal-Alameda Co. |
| Estes | 2 | Survivors of Serviceman | X | X | | | Crossroads | 1946 | USDC N.D. Cal. |
| Ferguson | 2 | Survivors of Serviceman | X | X | | | Crossroads | 1946 | USDC N.D. Cal. |
| Guarisco | 1 | Serviceman | | X | | | Crossroads | 1946 | Cal.-Alameda Co. |
| Hendrix | 1 | Survivor of Serviceman | | X | | | Crossroads | 1946 | Cal.-Alameda Co. |
| Milne | 4 | Survivors of Serviceman | | X | | | Crossroads | 1946 | Cal.-San Francisco Co. |
| Paskett | 4 | Survivors of Serviceman | | X | | | Crossroads | 1946 | Cal.-San Francisco Co. |
| Piccinino | 1 | Survivor of Serviceman | X | X | | | Crossroads | 1946 | USDC N.D. Cal. |
| Saraiva | 5 | Survivors of Serviceman | | X | | | Crossroads | 1946 | USDC N.D. Cal. |
| Seveney | 1 | Survivor of Serviceman | X | | | | Crossroads | 1946 | USDC D.R.I. |
| Van Winkle | 1 | Survivor of Serviceman | X | X | | | Crossroads | 1946 | USDC N.D. Cal. |
| Williams | 1 | Survivor of Serviceman | | X | X | X | Greenhouse | 1951 | USDC N.D. Cal. |
| Antolok/Alee | 2472 | Marshallese | | X | X | X | Castle | 1946-1958[d] | USDC N.D. Cal. |
| Antolok/Alee | 2472 | Marshallese | X | | | | Castle | 1946-1958[d] | USDC N.D. Cal. |
| Curbow | 5 | Servicemen | | X | X | X | Castle | 1954 | USDC C.D. Cal. |
| King | 2 | Survivors of H&N employee | | X | X | X | Castle, etc. | 1954-1958 | USDC N.D. Cal. |
| Porambo | 1 | Survivor of Serviceman | X | X | | | Castle | 1954 | Cal-San Francisco Co. |
| Stevens | 3 | Survivors of H&N employee | | X | X | X | Castle | 1954 | USDC N.D. Cal. |
| Kuhn | 1 | H&N employee | X | | | | Wigwam, etc. | 1955-1960 | USDC N.D. Cal. |
| McCarthy | 2 | Survivor of Serviceman | X | X | X | X | Wigwam | 1955 | USDC D.N.J. |
| Runnels | 5 | Survivor of Serviceman | X | | | X | Wigwam | 1955 | USDC D. of Hawaii |
| Dixon | 5 | Survivor of Serviceman | X | X | X | X | Redwing | 1956 | USDC N.D. Cal. |
| Hill | 1 | Serviceman | X | X | X | X | Hardtack I | 1958 | USDC E.D. N.C. |
| Fassett | 3 | Survivor of Serviceman | | X | X | X | Dominic I | 1962 | Cal.-San Francisco Co. |

Totals: 36 cases, 6,495 plaintiffs, USA-23, UC-29, SNL-11, others-14.

[a]Current-October 1983. Source: Semiannual Litigation Report, September 30, 1983, Office of Chief Council, U.S. Department of Energy.

[b]U.C. is the University of California, operation of Los Alamos National Laboratory (formerly Los Alamos Scientific Laboratory) and other weapons research laboratories.

[c]SNL is Sandia National Laboratory operated by Western Electric, a subsidiary of American Telephone and Telegraph.

[d]Antolok and Alee. Class action lawsuits on behalf of Marshallese subjected to radioactive fallout primarily as a result of CASTLE-Bravo (1954).

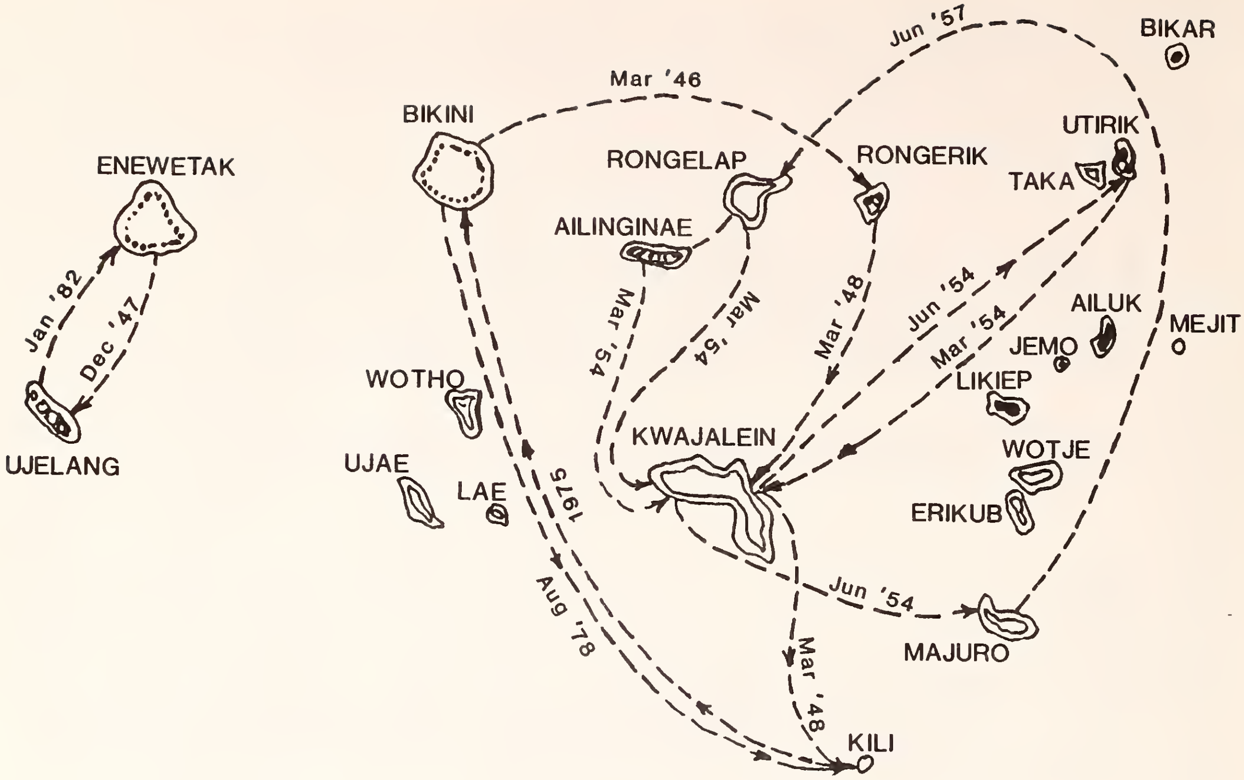



Figure V-11. Movement of Marshallese people because of United States Nuclear Weapons testing in the Pacific (adapted from Lessard 1983).

for example, Branch (1980) presented arguments against the concept of Insular Cases for the people of the northern Mariannas who were also part of the Trust Territory of the Pacific Islands. Regardless, the displacement of some residents of the Marshall Islands has turned out to be a long ordeal that is proving difficult to bring to a satisfactory conclusion. Their major movements from 1948 to 1958 that were a direct result of the United States nuclear weapons program are outlined in Figure V-11.

Summary Perspectives and Research Needs

It is unfortunate that decisions that seemed reasonable in 1946 concerning the development and testing of nuclear weapons in the Marshall Islands could have such large repercussions 35 years later. The United States had just emerged from World War II and was developing a new role in the post-war world. Certainly the task of developing nuclear weapons capability was formidable and required a substantial commitment of people and resources. These commitments are being viewed with a different perspective today, especially by people in a position to receive financial gain in return for earlier sacrifices made by themselves or by their family members. It is difficult to project how to fairly compensate the Marshallese for the use and disruption of their home islands in light of current social concerns.

Regarding ex-servicemen that participated in Oceanic Nuclear Weapon Tests, there will probably be many more lawsuits. It is a statistical probability that about 20% of the total population will eventually die of some form of spontaneous cancer. As the population of former test participants ages, and more normally develop cancer, the number of lawsuits is very likely to

increase. When individuals develop fatal diseases, it is typical to attribute their misfortune to some outside agent or source. Because radiation is known to cause cancer, and little of this risk is understood by the general population, it is likely that a large number of the 230,000 nuclear weapons test participants will eventually attribute their diseases to participation in the nuclear weapons tests. If pending litigations decide that the National Laboratories and other Government contractors are liable in light of the Federal Tort Claims Act, then thousands of lawsuits may eventually be filed.

Regardless of the final legal decisions concerning the Marshall Islands Plebiscite, the Federal Government should continue to support medical studies and care of the Marshallese population exposed to fallout. Some investigators have suggested that additional research efforts should be applied to the residents of Likiep Atoll. One reason to support these studies is to assure continuity with information obtained in the past.

When the Nuclear Test Personnel Review completes all of its planned reports describing nuclear weapons tests, it will be more convenient for people to learn about events that took place from 1946 to 1962. Making dosimetry records readily available will be a valuable aid to medical physicians and lawyers for both plantiffs and defendants, and the test participants.

An important observation in reviewing all aspects of nuclear weapons-related activities is our inability to decontaminate large areas. This is especially obvious at both Enewetak Atoll and at Palomares, Spain. Methods for large area decontamination need to be developed, both for remedial actions and for potential future incidents.

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SECTION VI

ROCKY FLATS NUCLEAR WEAPONS FACILITY

The Rocky Flats plant is located 16 miles northwest of downtown Denver. It is owned by the United States Government, and its primary purpose is to make plutonium components for nuclear weapons (U.S. Department of Energy 1980). Weapons components made at Rocky Flats are shipped to other plants in the United States for final assembly. Before construction of the Rocky Flats plant, plutonium components for weapons were manufactured primarily at the Los Alamos National Laboratory in New Mexico, and at the Hanford Atomic Products Operation near Richland, Washington. The United States Government approved construction of the Rocky Flats plant in 1951, and limited operations began in 1952. The original site occupied 2520 acres, and this was enlarged to 6550 acres in 1974 by adding a buffer zone. The present site layout is shown in Figure VI-1.

The U.S. Department of Energy is responsible for administrative control of the Rocky Flats facility. It acts through the Albuquerque Operations Office and Rocky Flats Area Office. Dow Chemical Company was prime contractor for the plant and operated it until July 1975, when the Atomics International Division of Rockwell International became the new prime contractor. Employment at Rocky Flats has averaged about 3,000 workers, but an additional 300 construction workers are on-site much of the time.

In addition to producing plutonium components for nuclear weapons, the Rocky Flats plant also manufactures uranium, beryllium, and stainless steel components. Obsolete weapons in the U.S. arsenal are returned to the plant for reprocessing to recover plutonium and americium. To assist in these activities, Rockwell International maintains large support groups in nuclear safety, engineering, health physics, environmental science, chemistry, and physics research.

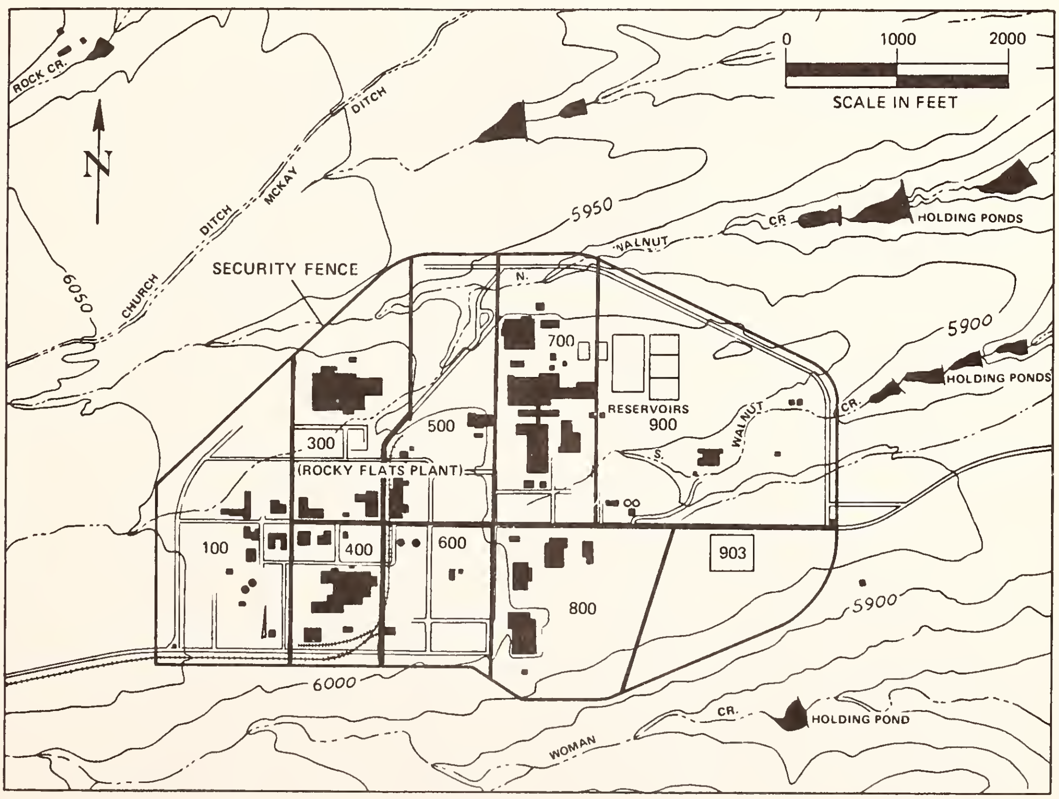



Figure VI-1. Map of Rocky Flats facility showing the main plant, security fence, and surrounding areas (U.S. Department of Energy 1980).

The largest population center near the Rocky Flats facility is the Denver Metropolitan Area. It now includes about 1.7 million people and is expected to reach 2.4 million people by the year 2000. Smaller population centers near Rocky Flats, their populations and distances from the plant are shown in Table VI-1 and Figure VI-2. Several ranches that produce cattle, dairy products, food crops, and horses are also located within 15 km of the plant site.

A major litigation began in 1975 concerning radioactivity, mainly plutonium, that was released from the Rocky Flats facility and deposited on nearby land. Several owners of land at the south and east boundaries of the facility have alleged that this land has lost value because the plutonium represents a health hazard and because its presence has resulted in restrictions on future use of the land. The United States Government, DOW Chemical Company, and Rockwell International are defendants in this litigation.

Releases of Radioactivity from the Rocky Flats Facility

Radioactivity has been released to the environment from the Rocky Flats facility during normal operations and as a result of accidents (Table VI-2). Normal operational releases of plutonium and uranium occurred through exhaust stacks on buildings, and the amount released was calculated from measurements of the total air flow and the amount of radioactivity per unit volume of air.

The largest single release of plutonium was accidental. Waste barrels containing small amounts of plutonium, machine cutting oil, and organic solvents leaked onto the ground in an open area located on the east side of the plant site. The leakage probably began in 1958 and was first noticed in 1959, but significant deterioration of the barrels did not appear until 1964. All of the waste barrels were removed by 1968, and the cleanup was completed by the end of 1969. Although it is impossible to determine the time sequence over which the off-site dispersion of plutonium occurred, air monitoring data obtained downwind from the barrel storage area indicated

Table VI-1
Population Centers Larger than 10,000 People Within 35 km of the Rocky Flats Plant (U.S. Department of Energy 1980)

| Community | Distance (km) | Direction | 1977 Population |
|---|---|---|---|
| Arvada | 14 | SE | 90,000 |
| Aurora | 34 | SE | 127,500 |
| Boulder | 16 | NNW | 90,400 |
| Broomfield | 11 | ENE | 20,600 |
| Commerce City | 24 | ESE | 16,300 |
| Denver | 25 | SE | 530,600 |
| Englewood | 32 | SSE | 33,100 |
| Golden | 14 | S | 11,200 |
| Lakewood | 19 | SSE | 134,300 |
| Littleton | 35 | SSE | 28,400 |
| Longmont | 32 | N | 38,200 |
| Northglenn | 18 | E | 33,100 |
| Thornton | 18 | E | 34,000 |
| Westminster | 14 | ESE | 45,000 |
| Wheatidge | 16 | SSE | 33,800 |

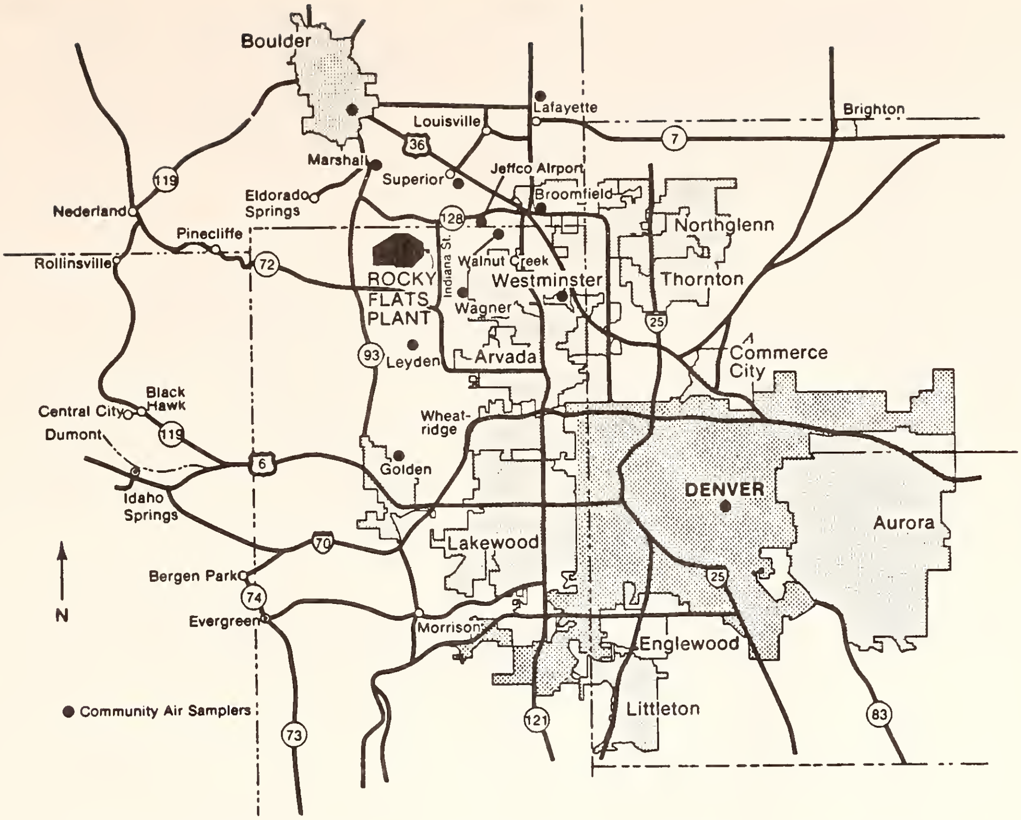



Figure VI-2. Map of communities surrounding the Rocky Flats facility (U.S. Department of Energy 1980).

that high levels of airborne plutonium coincided with winds that followed cleanup activity in the area (Figure VI-3) (Seed et al. 1971). This information suggests that most of the off-site dispersion of plutonium occurred during late 1968 and 1969. Studies of the distribution of plutonium in sediments of Standley Lake support this finding (Hardy et al. 1978).

The amount of plutonium that leaked onto the soil was estimated by Krey (1976). He used soil concentration measurements, beginning at the barrel storage area and extending out to 70 km from the plant, to estimate plutonium iso-concentration contours. Areas surrounded by the contours were integrated and then multiplied by the average plutonium concentration for each area. Using this method, Krey estimated that 11.4 Ci remained in soil on Rocky Flats property and approximately 3.4 Ci of plutonium was resuspended and deposited on ground surfaces beyond the plant boundary.

Two large releases of tritium, $^{3}H$, have also occurred from the Rocky Flats plant. An accident in 1968 led to the release of several hundred curies and another in 1973 released 500 to 2000 Ci. The release in 1973 occurred when material unknown to be contaminated with tritium was inadvertently processed. It was estimated that about 60 Ci of tritium was released in water effluents, 100 to 500 Ci was retained in ponds and tanks on-site, and the remainder escaped into the atmosphere. These releases of tritium are not as important as the plutonium releases in assessing health risks related to the Rocky Flats plant. Unlike the plutonium-contaminated soil described earlier, airborne tritium disperses widely in the atmosphere and may never redeposit on ground surfaces. In addition, tritium decays by emitting low-energy beta radiation that is less damaging to body tissues than the high-energy alpha radiation emitted by plutonium. For these reasons, the releases of plutonium along with smaller amounts of americium are more important potential hazards.

Table VI-2

Radioactivity (μCi) Released Annually from the Rocky Flats Plant[a]

| | Normal Operations | | | Accidental Releases | |
|---|---|---|---|---|---|
| Year | $^{238}U$ | $^{235}U$ | $^{239}Pu$ | $^{239}Pu$ | $^{3}H$ |
| 1953 | | | 2 | | |
| 1954 | | | 60 | | |
| 1955 | | | 70 | | |
| 1956 | | | 230 | | |
| 1957 | 40 | 230 | 1600 | 25,000 | |
| 1958 | 50 | 310 | 3100 | 3,400,000 | |
| 1959 | 30 | 540 | 1400 | | |
| 1960 | 60 | 860 | 1300 | | |
| 1961 | 520 | 480 | 1500 | | |
| 1962 | 370 | 250 | 3000 | | |
| 1963 | 340 | 280 | 3900 | | |
| 1964 | 240 | 190 | 2700 | 10 | |
| 1965 | 280 | 190 | 5300 | 1,200 | |
| 1966 | 140 | 230 | 320 | | |
| 1967 | 140 | 110 | 400 | | |
| 1968 | 140 | 160 | 490 | | < 1000 |
| 1969 | 170 | 50 | 780 | 880 | |
| 1970 | 190 | 60 | 350 | 25 | |
| 1971 | 60 | 40 | 70 | 10 | |
| 1972 | 40 | 4 | 60 | 2 | |
| 1973 | 60 | 10 | 80 | | 1000 |
| 1974 | 10 | 30 | 20 | 930 | 10 |
| 1975 | 30 | 30 | 10 | | 2 |
| 1976 | 10 | 20 | 4 | | 1 |
| 1977 | 20 | 20 | 4 | | .5 |

[a]Adapted from U.S. Department of Energy 1980.

Measurements of Plutonium and Americium in Soil

For the reasons noted above, most studies of radioactivity in soil near the Rocky Flats plant have focused on measurements of plutonium and americium. By weight, the plutonium is 93.8 percent $^{239}Pu$, 5.8 percent $^{240}Pu$, and 0.4 percent $^{241}Pu$ with trace amounts of $^{238}Pu$ and $^{242}Pu$ (U.S. Department of Energy 1980). Plutonium-241 decays by beta emission to $^{241}Am$, with a radioactive half-life of 13 years. Characteristics of these radionuclides are shown in Table VI-3. Americium-241 radioactivity currently amounts to 15 percent of the plutonium radioactivity, but through further decay of $^{241}Pu$ and because of its higher specific activity compared to $^{239}Pu$, its radioactivity will eventually become nearly equal to that of the plutonium in soil near Rocky Flats.

Measurements of radioactivity in the environment near Rocky Flats to determine the amount released from the plant are complicated by the presence of nuclear weapons test fallout and by the migration of radioactivity both in and with soil. Nuclear weapons fallout contributes only a small portion of the total plutonium and americium deposited near the east boundary of the plant

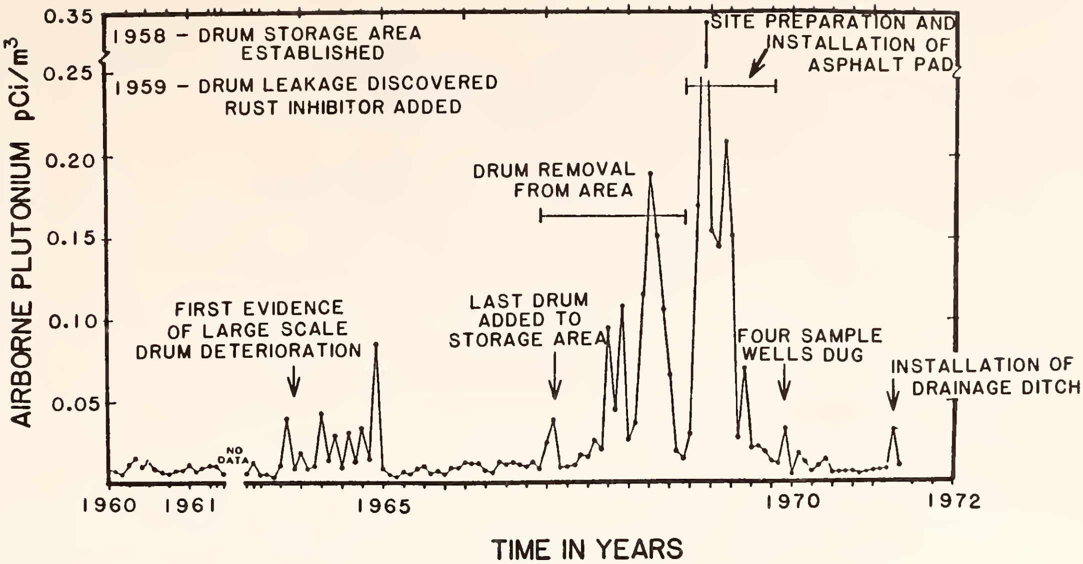



Figure VI-3. Monthly average air concentrations of plutonium east of the waste barrel storage area at Rocky Flats between 1960 and 1971 (Seed et al. 1971).

Table VI-3

Radioactive Characteristics of Plutonium and Americium Isotopes

| Isotope | Principal Emissions | Isotope Half-life (years) | Daughter Product | Daughter's Half-life (years) |
|---|---|---|---|---|
| $^{238}Pu$ | α - 5.5 Mev | 84 | $^{234}U$ | $2.5 \times 10^5$ |
| $^{239}Pu$ | α - 5.1 Mev | 24400 | $^{235}U$ | $7.1 \times 10^8$ |
| $^{240}Pu$ | α - 5.1 Mev | 6580 | $^{236}U$ | $2.4 \times 10^8$ |
| $^{241}Pu$ | β - 0.02 Mev | 13 | $^{241}Am$ | 458 |
| $^{242}Pu$ | α - 4.9 Mev | $3.8 \times 10^5$ | $^{238}U$ | $4.5 \times 10^9$ |
| $^{241}Am$ | α - 5.5 Mev | 458 | $^{237}Np$ | $2.2 \times 10^6$ |

site, but it accounts for the largest portion in soil in the Denver Metropolitan Area. To determine what fraction of the total plutonium in these areas originated from the Rocky Flats plant, special measurement techniques were developed based on the isotope mass ratio of $^{240}Pu$ to $^{239}Pu$ (Krey 1976). This ratio is 0.06 for Rocky Flats-derived plutonium and 0.16 for plutonium in nuclear weapons fallout. Therefore, soil samples should have $^{240}Pu/^{239}Pu$ ratios between 0.06 and 0.17 and measured values can be used to identify the origin of the plutonium. Other techniques using ratios of plutonium to strontium or americium have been less successful.

Transport by water, soil erosion, and digging by small animals all cause plutonium and americium to migrate downward in soil. Thus, soil samples must be taken to depths of about 20 cm to account for the total amount present at any site. Some studies have focused just on plutonium associated with very fine soil particles on ground surfaces since it has been suggested that this fraction is more likely to be resuspended by wind and then inhaled by people (Johnson et al. 1976). The measurements of plutonium in fine particle samples of surface soil have sometimes yielded higher concentrations of plutonium per unit mass, but they only account for a small portion of the total plutonium present. To determine the average amount of plutonium in soil that

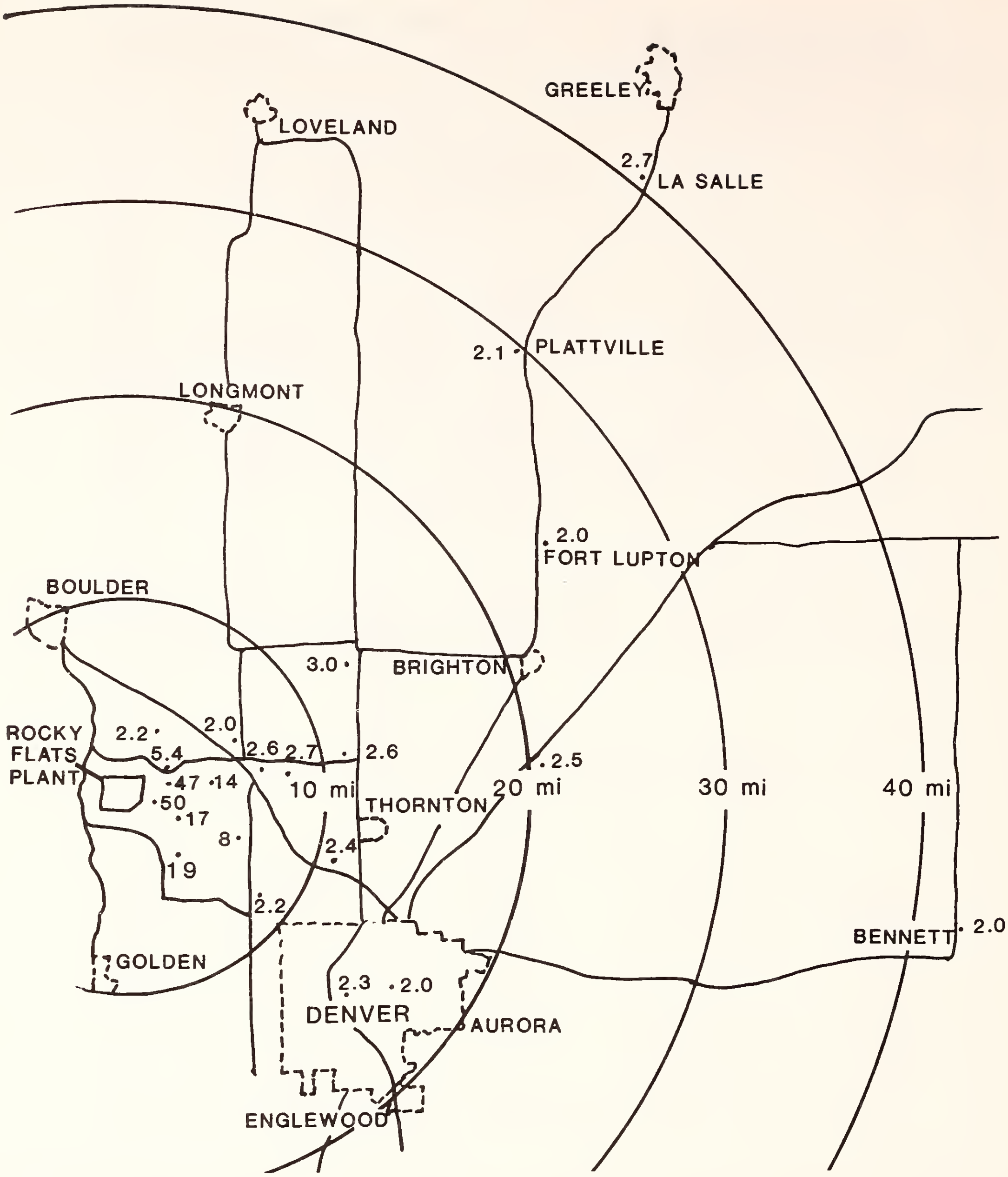
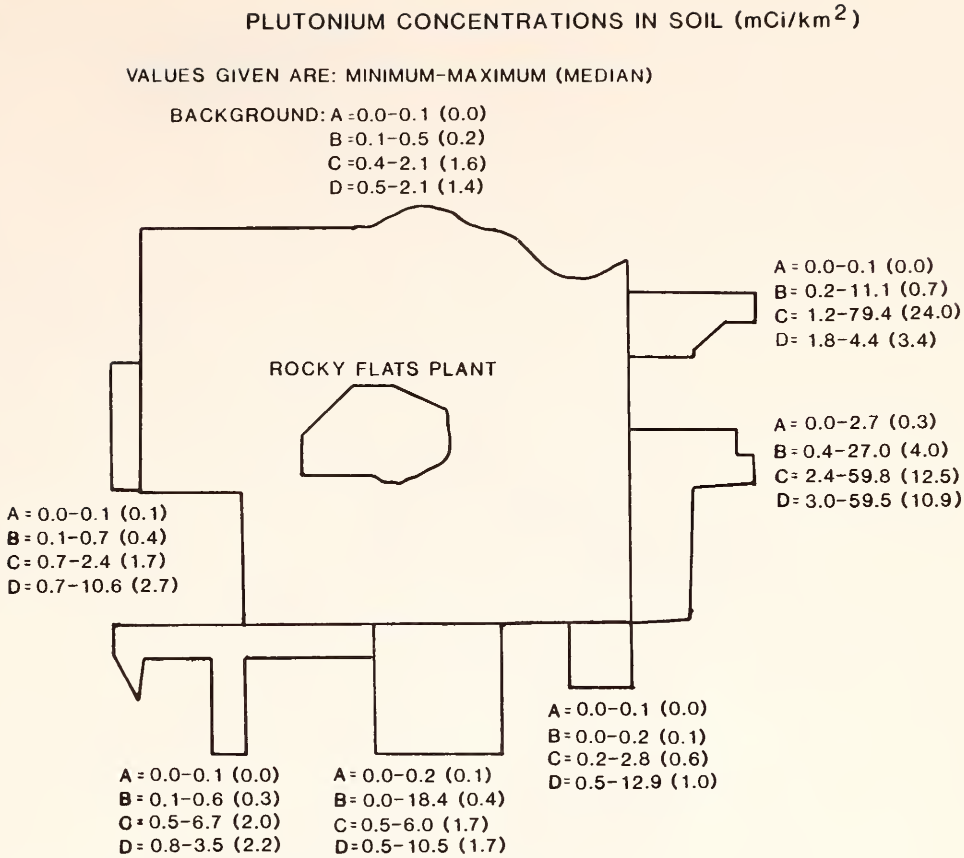



Figure VI-4. Measured plutonium concentration (mCi/km$^2$) associated with soil 0 to 20 cm in depth (Krey and Hardy 1970). Data from the AEC Health and Safety Laboratory (HASL) presently called Environmental Measurements Laboratory (EML).

is characteristic of a parcel of land near the Rocky Flats plant requires many measurements, because the action of wind blowing and accumulating soil deposits has caused considerable variability in measured plutonium soil concentrations. In some areas, plowing of soil has even reduced measured plutonium concentrations below levels expected from nuclear weapons fallout. Finally, it should be noted that the radiochemical determination of plutonium concentrations in soil is a difficult procedure that contributes significantly to sample variability.

Despite the difficulties of measuring the amount of plutonium at specific locations downwind from the Rocky Flats plant, it is possible to indicate its general patterns of dispersion (Figure VI-4). Near the east security fence, plutonium concentrations range from 400 to 2000 mCi/km$^2$. On private land to the east of the Rocky Flats property, plutonium soil concentrations range from




A - Jefferson County Health Department sampling method: dust

B - Colorado Department of Health sampling method: 0.3 cm depth

C - Rocky Flats Plant sampling method: 5 cm depth

D - Rocky Flats Plant sampling method: 5-20 cm depth

Figure VI-5. Measured plutonium concentrations in soil on private lands bordering the Rocky Flats facility.

20 to 50 $mCi/km^2$. Between 5 and 10 miles to the east of the plant, these concentrations fall to between 2 and 3 $mCi/km^2$; in Denver, plutonium soil concentrations are only about 2 $mCi/km^2$. Nuclear weapons test fallout accounts for about $1.7 \pm 0.5$ $mCi/km^2$ of plutonium in all of these areas (Krey 1976). Americium-241 radioactivity is about 15 percent of the plutonium radioactivity levels in these areas.

A more detailed study of plutonium and americium concentrations on private lands bordering the Rocky Flats plant was conducted by the U.S. Department of Energy as part of the land owners' litigation. Several analytical methods were used that included collecting samples of fine particles of surface soil and of bulk soil from layers 0 to 0.3 cm, 0 to 5 cm, and 5 to 20 cm in depth. The samples were randomly coded so that the analyst would not know what type of sample was being analyzed. One commercial laboratory performed the analyses on the complete series of samples, but several split samples were also analyzed by other laboratories to obtain an interlaboratory calibration. Results from these analyses are shown in Figures VI-5 and VI-6. Variability among the measurements for each parcel of land due to environmental factors is large, with the highest and lowest values being 3 to 5 times larger or smaller than the median values. Americium-241 concentrations were 10 percent to 20 percent of the Pu concentrations.

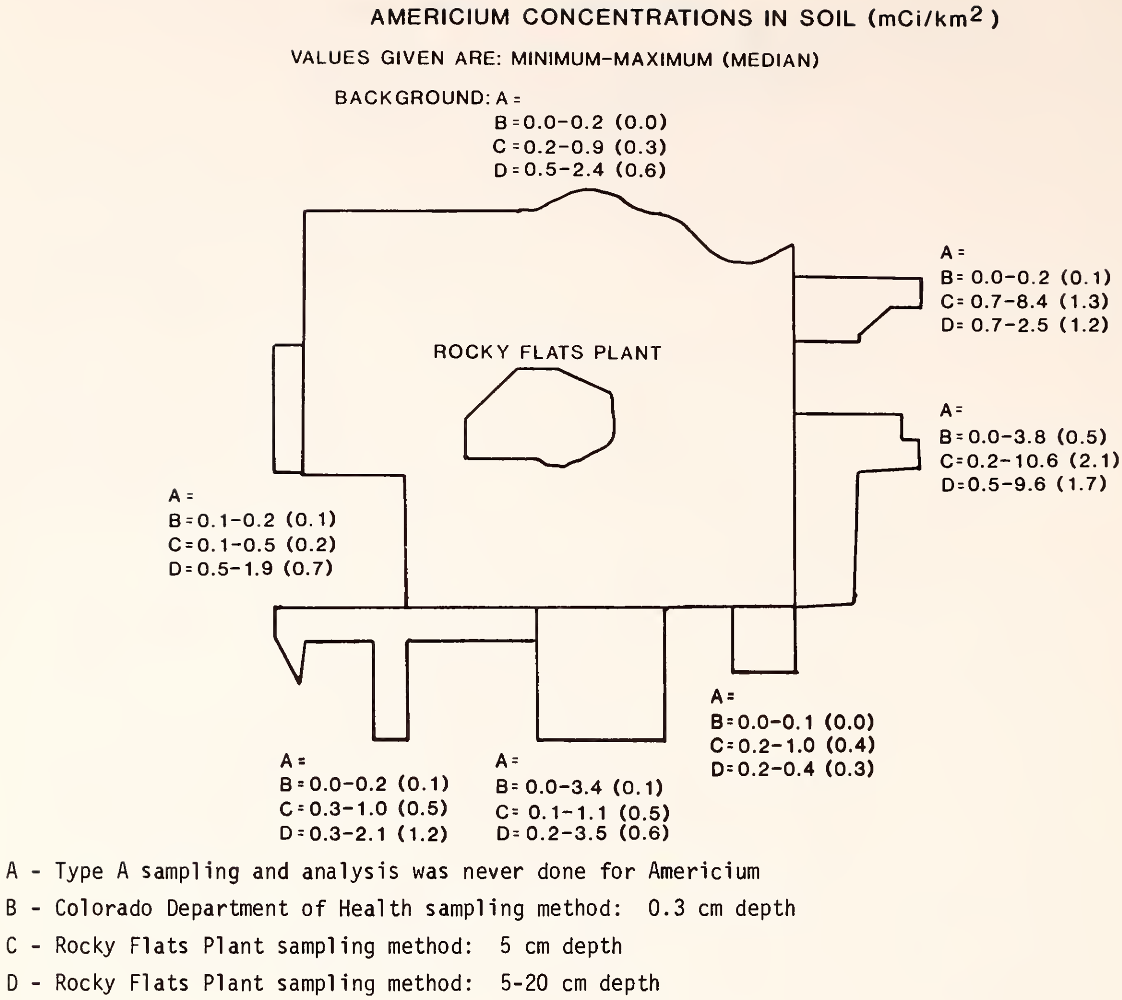



Figure VI-6. Measured americium concentrations in soil on private lands bordering the Rocky Flats facility.

## Plutonium Concentrations in Air

Two major atmospheric sampling programs have been operated to determine the concentrations of radioactivity in air near the Rocky Flats plant and nearby communities. The largest sampling network is maintained by the Rocky Flats Environmental Analysis Section and has samplers located at 35 different sites. Air samples are collected on filters that are analyzed weekly, and the average annual air concentrations of plutonium are reported (Rocky Flats Plant, Environmental Analysis Section 1975 to 1982).

The Environmental Measurements Laboratory, supported by the U.S. Department of Energy also operates air samplers near the Rocky Flats plant. This program, begun in 1970, uses sampling devices similar to those used in a worldwide network for monitoring nuclear weapons test fallout. Results of this program are also reported annually (Environmental Measurements Laboratory 1981, 1982).

The data produced by these air sampling programs are too extensive to summarize here, but typical results are shown in Figures VI-7a and VI-7b. In general, the samplers operated by the Environmental Measurements Laboratory and the Rocky Flats plant have shown similar air concentrations of plutonium. Measurements from all samplers indicate that air concentrations of

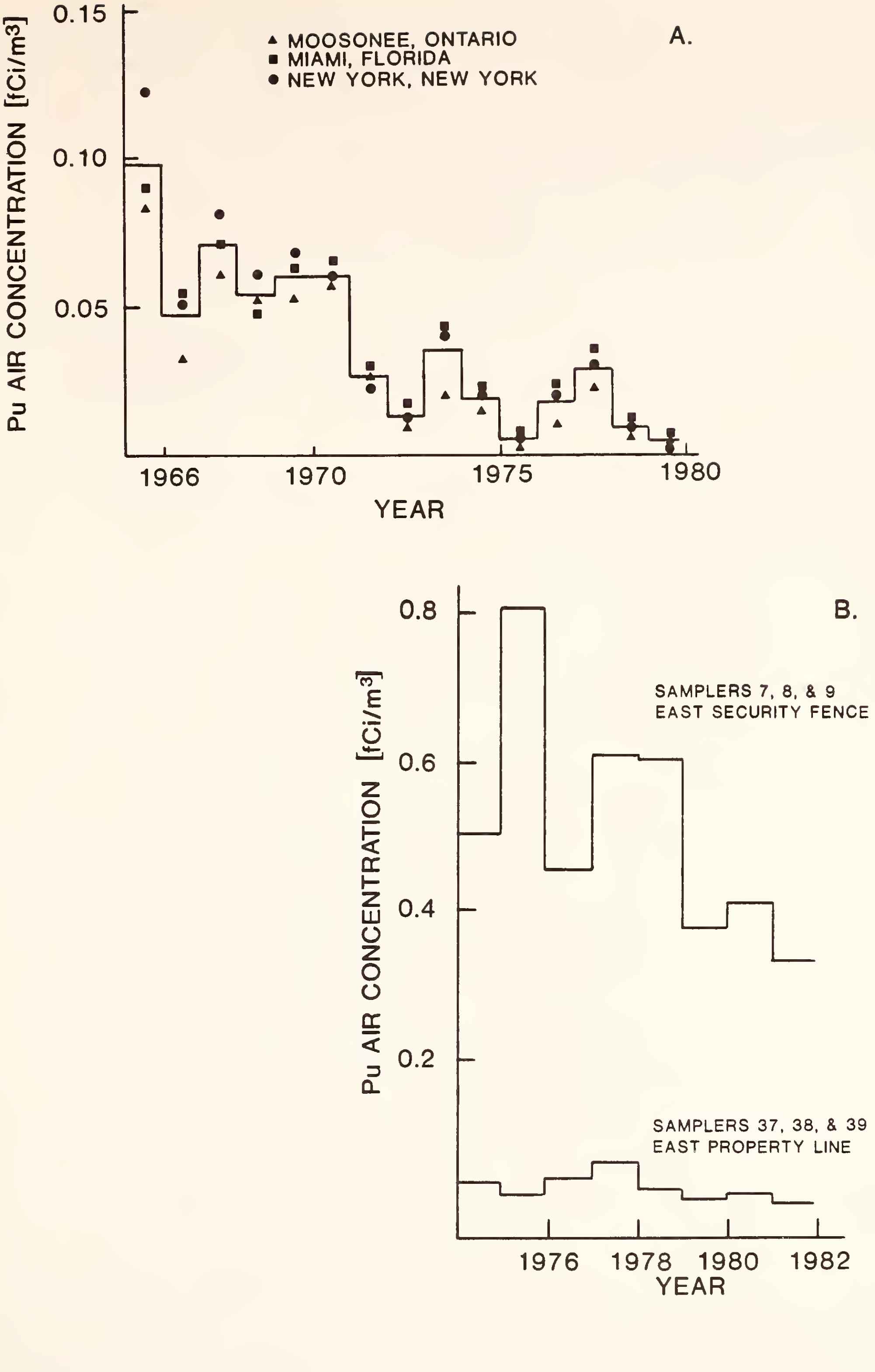



Figure VI-7. Plutonium air concentrations measured ($fCi/m^3$) near Rocky Flats and other United States cities. Figure 7A shows data from 1965-1980 for three Eastern cities of North America (Environmental Measurements Laboratory 1981, 1982). Figure 7B shows Rocky Flats data at the east security fence and at the east property line for 1975-1982 (Rocky Flats Plant, Environmental Analysis Section, 1975 to 1982).

plutonium both from fallout and from the Rocky Flats plant are decreasing with time. However, air samplers located immediately downwind from the former barrel storage area continue to show higher plutonium air concentrations than observed at the perimeter of the Rocky Flats plant or in nearby communities. Plutonium air concentrations near the east and south boundaries of the facility are now about equal to worldwide fallout levels and are relatively independent of plutonium soil concentrations in the immediate areas (Table VI-4).

Table VI-4
Plutonium in Soil and Air During 1975-1982

| Site | Median Soil Concentration $mCi/m^2$ | Average Air Concentration $fCi/m^3$ | Air Concentration[a] / Soil Concentration |
|---|---|---|---|
| Section 6 | 0.027 | 0.026 | $1.0 \times 10^{-9}$ |
| Section 7-18 | 0.023 | 0.030 | $1.3 \times 10^{-9}$ |
| Section 24 | 0.0016 | 0.027 | $1.6 \times 10^{-8}$ |
| Section 23 | 0.0034 | 0.032 | $0.9 \times 10^{-8}$ |
| Section 21-22 | 0.0042 | 0.031 | $0.7 \times 10^{-8}$ |
| Denver | 0.0018 | 0.024 | $1.3 \times 10^{-8}$ |
| Boulder | 0.0016 | 0.026 | $1.6 \times 10^{-8}$ |

[a]Given in units of [$fCi/m^3$ in air per $fCi/m^2$ on soil].

Plutonium in Tissues of Rocky Flats Area Residents

An extensive study was conducted to determine if plutonium released from the Rocky Flats plant could be detected in the bodies of area residents (Cobb et al. 1982). Although Rocky Flats plutonium has been measured in area soil and air, increased health risks to residents would occur only if sufficient quantities were deposited within the residents' tissues. The technique used to detect Rocky Flats plutonium in the presence of fallout plutonium in body tissues was similar to that used by Krey (1976) in the studies of soil. Mass spectrometry was used to measure the $^{240}Pu/^{239}Pu$ ratios, and radiochemistry was used to measure the total plutonium.

Plutonium concentrations were reported for lung and liver samples. The tissues were obtained at autopsy from area residents who had lived at known locations near the Rocky Flats plant for specified periods of time before death. People who had lived more than 50 km from the plant were considered to be a control population because they would not have had significant exposure to Rocky Flats plutonium. A summary of some results from this study is given in Table VI-5. In general, no statistically significant relationships were found between measured concentrations of plutonium in lung or liver samples and distance of residence from the Rocky Flats plant. This was also true for the $^{240}Pu/^{239}Pu$ ratio, although there was a tendency for people who lived closer to Rocky Flats to have a somewhat lower $^{240}Pu/^{239}Pu$ ratio for lung samples than those who lived further away. No explanation was given for the different ratios observed in lung and liver samples or for the ratios in liver that exceeded worldwide fallout at 0.17. These observations suggest some analytical problems. The strongest statistical correlations were found between the plutonium concentration measurements and age and smoking histories. It was also noted that people living in the Denver area had similar tissue concentrations to people living in other areas of the United States (McInroy et al. 1979).

Table VI-5

Plutonium Measurements of Tissues Obtained from Rocky Flats Area Residents Classified by Area of Residence During Last 5 Years of Life (Cobb *et al*. 1982)

| Area of Residence | Lung dpm/organ | Lung $^{240}Pu/^{239}Pu$ | Liver dpm/organ | Liver $^{240}Pu/^{239}Pu$ |
|---|---|---|---|---|
| Within 25 km of Rocky Flats | 0.357[a] | 0.149 | 3.046 | 0.200 |
| Between 25 and 50 km from Rocky Flats | 0.323 | 0.162 | 3.150 | 0.195 |
| Beyond 50 km from Rocky Flats in Colorado | 0.378 | 0.157 | 3.583 | 0.202 |
| Outside Colorado | 0.420 | 0.170 | 3.857 | 0.191 |

[a]Standard deviations of the organ burden measurements generally ranged between 60% and 90% of the average values, and for the $^{240}Pu/^{239}Pu$ ratios, between 15% and 30% of the average values.

## Radiation Doses to Denver Area Residents from Internally Deposited Plutonium

The levels of radiation exposure to Rocky Flats area residents from the total amount of internally deposited plutonium are well known (National Research Council 1980, Cobb *et al*. 1982, McInroy *et al*. 1979). However, it is not known what fractions of these exposures result from plutonium released from the Rocky Flats plant. This fraction must be a small part of the total exposure because (1) air concentrations of plutonium at the plant boundary are similar to those measured in Denver and Boulder, (2) tissue analyses did not indicate a significant change in plutonium concentration or in the $^{240}Pu/^{239}Pu$ ratio for people who lived at different distances from Rocky Flats, and (3) people living in the Denver area have similar tissue plutonium concentrations to people who live in other areas of the United States.

Radiation doses to the lungs and liver of Denver area residents are summarized in Table VI-6. The total plutonium-related doses are 0.6 mrem/yr to lungs and 3 mrem/yr to liver. These doses are only about 1 percent of natural background radiation doses and the largest fraction must be attributed to nuclear weapons test fallout not to plutonium released from the Rocky Flats plant. Also, there is no evidence that people who might live adjacent to the Rocky Flats facility in the future would receive higher radiation exposures from the released plutonium than estimated in the studies described above. The highest potential for exposure occurred when the plutonium first dispersed from the plant site and before it deposited on ground surfaces. Environmental weathering of the ground deposits generally makes them less available for resuspension as time passes.

## Surveys of Cancer Distribution Patterns in the Denver Area

Two surveys of cancer distribution patterns in the Denver area related to radioactivity released from the Rocky Flats plant have been reported (Johnson 1981, Chinn 1981). Both studies used cancer incidence data obtained from the National Cancer Institute's Third National Cancer Survey for the period 1969 to 1971, and they attempted to relate cancer incidences for different census tracts to plutonium iso-concentration contours that were originally developed by Krey (1976), and later modified by Johnson (1981). Both studies concluded that there was an excess of cancers caused by radioactivity released from Rocky Flats in the area that extended about 21 km to the southeast of the plant in the direction of Denver. This area is in the direction of the

Table VI-6

Radiation Exposures and Doses to Denver Area Residents from Plutonium and Natural Background

A. Internally Deposited Plutonium

| | | |
|---|---|---|
| Measured air concentration 1975-1980 | 0.025 $fCi/m^3$ | [0.004-0.06][a] |
| Measured lung burdens 1975-1980 | 160 fCi | [50-430] |
| Measured liver burdens 1975-1980 | 1600 fCi | [500-3000] |
| Calculated dose rate to lung | 0.03 mrad/yr<br>0.6 mrem/yr | [0.01-0.08] |
| Calculated dose rate to liver | 0.15 mrad/yr<br>3.0 mrem/yr | [0.05-0.30] |

B. Background Radiation[b]

| | |
|---|---|
| Estimated dose Rate to lung | 180-530 mrem/yr<br>(100-450 mrem/yr from alpha) |
| Estimated dose Rate to liver | 80 mrem/yr |

[a]Approximate 95 percentile range.

[b]Values obtained from National Research Council 1980.

prevailing wind from the Rocky Flats plant estimated from data for 1953 to 1970 (Krey 1976). This area was bounded by the 0.8 $mCi/km^2$ plutonium soil iso-concentration contour drawn by Johnson. However, people living in the eight census tracts nearest to Rocky Flats, bounded by the 1.3 $mCi/km^2$ contour reported by Krey (1976), had lower cancer incidences between 1969 and 1971 than expected by Johnson. About 125 cancers that occurred during the three-year period were attributed to exposures to plutonium by Johnson and Chinn. Although it was implied that other radioactive substances that have not as yet been detected also played a role in increasing area cancer incidences, the Rocky Flats facility does not normally handle large quantities of radioisotopes other than plutonium, americium, and uranium in unsealed sources. The accidents involving tritium are the only known exception, and these did not result in significant radiation exposures to people.

There are many difficulties in accepting the conclusions of Johnson and Chinn. Simple correlations between cancer incidences in populations and the locations of their residences with respect to Rocky Flats are not sufficient to establish a cause-effect relationship. Many meaningless correlations of this type occur. Cause-effect relationships must be based upon additional factors, including (1) the types of health effects observed should be typical of those caused by the toxic agent in question, (2) the levels of exposure should be sufficient to produce the effects, (3) the pattern of health effects among people of different ages, sexes, races, life styles and socioeconomic conditions should not differ without reason, and (4) the effects of confounding factors that could lead to similar results must be accounted for. None of these supporting factors are present in the studies of Johnson and Chinn.

The only types of cancers that have been related to exposures to plutonium are cancers of lung, bone, and liver. This information comes from studies in laboratory animals since increased incidences of disease have not been detected in people exposed to plutonium. Most of the excess

cancers reported by Johnson and Chinn are cancers of the gastrointestinal tract and the male reproductive system. No statistically significant increases were reported for cancers related to bone or liver. Also, the reported excess in respiratory tract cancers cannot be attributed to Rocky Flats plutonium because smoking is the overwhelming cause of lung cancers, and no information was available on smoking histories for the "exposed" and "unexposed" populations.

Plutonium concentrations in soil have been shown to decrease with increasing distance from the Rocky Flats plant; however, no such pattern was found for plutonium concentrations in tissues of area residents (Cobb _et al_. 1982). Therefore, no differences in radiation doses to the "exposed" and "unexposed" populations have been demonstrated. Because plutonium has a very long residence time in body organs, it is not likely that the high exposures to Rocky Flats plutonium suggested by Johnson and Chinn could have escaped detection in the study by Cobb _et al_.

The levels of excess cancer reported by Johnson and Chinn were 15 percent in males and 5 percent in females. An excess in lung cancer was reported only for males. Such sex differences in radiation sensitivity have not been reported previously except for thyroid cancer and cancers specific to reproductive organs. This discrepancy indicates that there are unaccounted confounding factors in the study, e.g., cigarette smoking, which make it impossible to attribute the reported excess of cancers to plutonium exposure with any degree of confidence.

It has been estimated that natural background radiation may account for about 1 percent of the natural cancer incidence in the United States (National Academy of Sciences 1980). Since cancer incidence has been described as being linearly related to radiation exposure at low dose levels (National Research Council 1972, 1980), the 10 percent increase for the "exposed" population reported by Johnson and Chinn would require radiation exposures 10 times as large as those from background radiation. No such exposures have been attributed to releases of radioactivity from the Rocky Flats plant. Therefore, exposures to Rocky Flats radioactivity are not sufficient to cause the health effects Johnson and Chinn reported.

Overall, cancer incidence distributions reported for Denver and the surrounding counties appear to be typical of the highly variable patterns that are found in many metropolitan areas in the United States (Cuddihy _et al_. 1979). Nonetheless, because of public concern over radiation exposures, additional studies were undertaken to further explore the relationships suggested by Johnson and Chinn between cancer incidence patterns in the Denver area and the location of the Rocky Flats plant and to determine if the cancer incidence patterns for 1969 to 1971 are consistent with similar data for 1979 to 1981 (Crump _et al_. 1984). The primary conclusions derived from these detailed statistical analyses are:

1. The most significant statistical correlation identified is between census tract cancer incidences and distance from the State Capitol Building (i.e., distance from the center of the Denver metropolitan area and therefore a measure of the urban effect).
2. For both 1969 to 1971 and 1979 to 1981, cancer incidences in census tracts within 10 miles of the Rocky Flats plant were no greater than those for the total Denver Standard Metropolitan Statistical Area.
3. In contrast to data for 1969 to 1971, between 1979 and 1981 cancer incidences in census tracts within Johnson's highest exposure area were less than cancer incidences in census tracts within lower exposure areas.
4. Statistical correlations between census tract cancer incidences and Johnson's exposure areas or other Rocky Flats-related variables largely disappear when the analyses are controlled for demographic and socioeconomic confounding factors.

In total, this study of cancer incidence patterns in the Denver area does not support the hypothesis that the Rocky Flats plant has caused excess cancers in nearby census tracts.

Radiation-Related Litigation Involving the Rocky Flats Plant

Two types of radiation-related litigation have involved the Rocky Flats plant during the last several years. The first alleges damage to private properties adjacent to the east and south boundaries of the plant site. Owners of these properties have claimed that negligent operation of the Rocky Flats plant led to the deposition of plutonium, uranium, and americium on their lands. The deposited radioactivity is said to have prevented them from realizing full benefit from unrestricted use of these properties. The alleged property value losses and exemplary damages amount to more than $25,000,000. The second type of litigation involves worker compensation claims alleging that over-exposures of Rocky Flats workers to ionizing radiation caused them to develop various types of fatal cancers. Because none of the workers were exposed to more radiation than permitted by applicable standards, these claims imply that cancer risks from radiation were markedly underestimated by those who established the standards.

A. The Property Owners' Litigation

In 1975, a complaint was filed in the United States District Court for the District of Colorado in behalf of plaintiffs Marcus F. Church, Marcus F. Church Trustees, William C. Ackard, Samuel Butler, Jr., and Butler Investments. The plaintiffs are owners of properties that border the Rocky Flats plant. Their complaint alleged that the United States Government, DOW Chemical Company, and Rockwell International operated the Rocky Flats plant in a manner that was negligent and caused events that now prevent the plaintiffs from developing their land to its full potential. The alleged negligent acts included improper handling of waste materials and accidents that caused fires leading to releases of plutonium, americium, and uranium into the environment. These radionuclides are said to have contaminated plaintiffs' lands in excess of state and federal statutes and industry standards. These conditions led the U.S. Department of Housing and Urban Development to require that potential borrowers for purchases of property near Rocky Flats be provided with a "Rocky Flats Advisory Notice." The Colorado Department of Health and local governments have also attempted to restrict development of land within 4 miles of the plant to open space or industrial use.

In 1972, the U.S. Environmental Protection Agency received a request from the State of Colorado to consider measures for the control of plutonium in soil and to evaluate health risks for people who live or would live in the vicinity of the Rocky Flats plant. As an interim measure in 1973, the Colorado Department of Health adopted a guideline for plutonium activity in soil at 2 dpm/g in the top 0.3 cm. For property exceeding this level, builders could be required to exercise special construction techniques to protect workers.

In September 1977, the U.S. Environmental Protection Agency completed a document, "Proposed Guidance on Dose Limits for Persons Exposed to Transuranium Elements in the General Environment." This guidance is based upon the criterion that no person should be exposed to plutonium or other transuranium elements in soil at levels that would cause a risk of more than $1 \times 10^{-6}$ per year of premature death from cancer. This level of risk was calculated to result from radiation doses of 1 mrad/yr to lung or 3 mrad/yr to bone. To implement this guidance, a soil screening level was recommended at 0.2 $\mu Ci/m^2$ in the top 1 cm of soil. The screening level indicated a concentration of alpha radioactivity in soil below which no remedial action or further analysis was required. If soil exceeded this level of transuranium element radioactivity, then further study would be required to assure that people would not be exposed to more than 1 mrad/yr to lung or 3 mrad/yr to bone.

The Colorado State guideline is set at a radioactivity level that is about 15 times lower than the U.S. Environmental Protection Agency soil screening level (Table VI-7) and the concentration of natural alpha radioactivity in soil caused by the presence of uranium, thorium, and actinium and their daughter radionuclides. Measurements of plutonium and americium

Table VI-7

Levels of Alpha Radioactivity in Soil Compared to Guidelines Recommended by the Environmental Protection Agency and Colorado State Department of Health

| | Radioactivity in Top 1 cm | |
|---|---|---|
| | $mCi/m^2$ | dpm/g soil |
| Natural radioactivity | | |
| (U, Th, and Ac Series) | 0.24 | 35 |
| Plutonium fallout | | |
| New York City | 0.003 | 0.4 |
| Denver | 0.002 | 0.3 |
| Rocky Flats boundary | 0.02 | 3 |
| Guidelines | | |
| EPA soil screening level | 0.2 | 29 |
| Colorado guideline[a] | 0.01 | 2 |

[a]Refers to transuranic radioactivity in top 0.3 cm of soil.

radioactivity on lands bordering the Rocky Flats facility are generally less than the Colorado state guideline, although one section of land had a median value 3.5 times higher. Some individual measurements of soil on properties bordering the facility had alpha radioactivity concentrations as much as 10 times the Colorado state guideline. Other sections of land are used for agriculture and have been plowed several times during the last ten years. This reduced the concentrations of plutonium in surface soil well below the concentrations expected from nuclear weapons test fallout alone. Thus, deep plowing of soil that has been watered to reduce dust resuspension is likely to be the most practical solution to reducing surface soil radioactivity if this should be deemed necessary.

Claims by the plaintiffs are summarized in Table VI-8. Testimony has been presented on measurements of plutonium and americium in soil obtained from plaintiffs' lands. Dr. Johnson testified that surface soil collected with a fine brush and pan is more representative of the soil fraction that can be resuspended by wind than are the deeper soil samples collected by the defendants or the Colorado State Department of Health. His analyses showed that some surface soil samples collected in this way had several times higher plutonium concentrations than those reported by the defendant. Thus, Dr. Johnson claimed that health risks to an exposed population would be underestimated by using analyses of deep soil samples and the risk models developed by the Environmental Protection Agency in deriving the proposed soil screening level.

Dr. John Gofman also testified for the plaintiffs. He stated that the soil sampling and analysis program conducted by the defendants was not scientifically valid and not suitable for evaluating health risks to people who would use the plaintiffs' lands. His criticisms focused on the particulate nature of plutonium in the soil, which may cause high variability among the samples analyzed and high local concentrations in small areas that could have been missed, considering the low density of sampling used. Mr. S. Chinn presented additional testimony about cancer distribution patterns in the Denver Metropolitan area related to distance and direction from the Rocky Flats plant. This study is discussed above.

Table VI-8

Summary of Claims for Relief Presented by Plaintiffs in Rocky Flats Land Owners' Litigation

| Type of Claim | Substance of Claim |
|---|---|
| 1. Negligence | Defendants did not use required care in handling plutonium and other ultrahazardous materials at the Rocky Flats plant. |
| 2. Strict liability | Plutonium and other radioactivity used at Rocky Flats are ultra-hazardous substances for which the defendants are liable, in any event, for its release and exposures of people. |
| 3. Trespass | Radioactivity from Rocky Flats entered the plaintiffs' land, water, and air without their permission. |
| 4. Nuisance | Operations at the Rocky Flats plant have been and continue to be a nuisance to the plaintiffs in attempting to gain full benefit from use of their properties. |
| 5. Exemplary damages | Damages should be awarded to discourage future similar acts. |
| 6. Declaratory judgments | Defendants damaged plaintiffs' properties in violation of statutes, regulations, and common law standards. |
| 7. Constitutional tort, inverse condemnation, implied contract and constitutional taking | The United States Government has taken plaintiffs' land without permission and without providing compensation. |
| 8. Tort claims and attorney's fees | Plaintiffs are entitled to recover damages from defendants. |

In response to these claims, the defendants did not deny that small but measurable amounts of plutonium and americium were released from the Rocky Flats plant and deposited on plaintiffs' lands. However, the defendants argued that the U.S. Environmental Protection Agency has the expertise to resolve these complex technical issues and valid authority to establish radiation exposure guidelines. The Agency's evaluation of the Rocky Flats plutonium and americium releases found no significant increase in health risk to people living nearby. Based upon this analysis and other analyses that produced similar results, the defendants argued that the plaintiffs' lands were unharmed and that no negligent acts had occurred. Other claims based upon nuisance, trespass, strict liability, and inverse condemnation were argued to be claims against the United States Government, for which no relief could be granted by the court. For these reasons, the defendants moved that the litigation be dismissed.

After a subsequent motion was filed by the plaintiffs claiming that the State of Colorado had exclusive authority to regulate plutonium on lands adjacent to the Rocky Flats plant, the court issued its decision dismissing all claims against the United States, DOW Chemical Company, and Rockwell International on May 27, 1982. The plaintiffs appealed the decision to the Tenth Circuit Court of Appeals, which reversed the trial court decision, and remanded the case back to the lower court for trial. Subsequently, the United States Government has offered to purchase plaintiffs' lands to the east of the Rocky Flats plant as part of a settlement of all related injury claims.

B. Workman's Compensation Hearings Involving Rocky Flats Employees

Several workman's compensation hearings involving former Rocky Flats employees who died of cancer are currently in progress. The cancers are alleged to be related to external gamma or X-ray exposures and internally deposited plutonium. None of the employees received radiation

doses in excess of occupational exposure standards (Code of Federal Regulations 1980). To be successful, the plaintiffs in these hearings must show that the cancers were, more likely than not, caused by the radiation exposures.

Because radiation does not cause unique and identifiable types of cancer, probability relationships between the levels of radiation dose received by individuals and cancer risk may be used to argue for or against a probable cause. These are referred to as calculations of attributable risk or assigned shares; however, this approach cannot identify with a high degree of certitude individual cancers that may have been caused by radiation exposures. Also, large discrepancies exist in the opinions of some scientists about the effectiveness of low doses of radiation in causing cancer which further complicates expert testimony on probable cause. Scientists who testified for the plaintiffs in these hearings are Dr. Alice Stewart, Dr. Carl Johnson, and Dr. Karl Morgan.

Dr. Alice Stewart has based most of her testimony on a radiation dose-effect model developed from an analysis of cancer incidence in Hanford workers. This analysis estimated the most likely values for the dose of radiation that would double the incidence of radiosensitive cancers, the duration of the latency period, the change in sensitivity with age of an individual, and a factor to account for non-linearity in the dose-effect relationship. These parameters are used in her calculations of attributable risk. Her analyses have been criticized because many scientists do not believe that a radiation dose-effect relationship has been established for the Hanford worker population and no effort has been made to estimate the uncertainty in the projected risks even though these appear to be very large, based upon a limited review of the uncertainties associated with two of the parameters (Gilbert and Marks 1979, Anderson 1978, Sanders 1978, Hutchison et al. 1979). Further analysis of this radiation effects model is being done to evaluate the total uncertainty in the model calculations (White et al. 1984).

Dr. Carl Johnson has testified about his studies of cancer incidence patterns in the Denver area. As discussed above, these studies claim to show that the incidence of radiosensitive cancers is higher than expected for populations living close to the Rocky Flats plant. In each case, this claim leads him to conclude that the radiation exposures received by the former Rocky Flats workers caused their cancers. Dr. Karl Morgan has developed testimony on dose calculations suggesting some workers received very high exposures from internal plutonium. His testimony has postulated high exposures that have not been supported by monitoring records, and the dose calculations have given results that were several orders of magnitude greater than those calculated by generally accepted methods (International Commission on Radiological Protection 1979).

Decisions have been rendered in only two of the workman's compensation hearings. In one case, the hearing officer ruled in favor of the claimant. However, this decision was reviewed by the Colorado Industrial Commission and the Colorado Court of Appeals, and has been returned for further consideration by an industrial claims review panel. The second case was dismissed for lack of evidence of work-related injury.

Lessons Learned from the Rocky Flats Land Owners' Litigation

The first important lesson learned from the Rocky Flats land owners' litigation is the value of good industrial housekeeping practices, especially in handling toxic waste disposal. The level of public awareness and sensitivity to toxic wastes in the environment is currently high and likely to increase in the future. Thus, quantities of materials released into the environment that may be considered small today could be viewed as major concerns at some time in the future. Therefore, special techniques should be developed to clean up environmental spills before they become widely dispersed. Studies should also be conducted on the efficacy of deep-plowing large areas of land as a means of reducing surface contamination of toxic wastes while minimizing resuspension and redistribution. In this respect, the area surrounding Rocky Flats can serve as a model for testing environmental cleanup techniques applicable to arid climates.

Second, the U.S. Department of Energy should support more efforts to obtain timely and impartial scientific reviews of epidemiologic studies of populations living near its facilities. Such reviews should be done as the studies first appear in the literature and not as a reaction to an adversary proceeding. They should be thorough, repeating the reported data analysis if necessary, and they should be accomplished through agencies such as the National Research Council or the National Institutes of Health. Careful documentation of these reviews should be made along with strong efforts to increase public awareness and knowledge of any controversial issues.

Finally, the U.S. Department of Energy should continue to insist that strong industrial hygiene and environmental monitoring programs be developed by contractors responsible for the operation of its facilities that handle radioactive materials and other toxic substances. Defense efforts by attorneys in the Rocky Flats land owners' litigation have been adequate largely because a record of well-documented environmental releases of radioactivity currently exists. Because the magnitudes and time histories of these releases are well-known, the impacts of unsupported speculations are minimized. To be most useful, environmental monitoring information should be accurate and timely and provide a sequential history of events or conditions from the start of a facility's operation. It is also useful if several laboratories participate in such monitoring programs.

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## SECTION VII

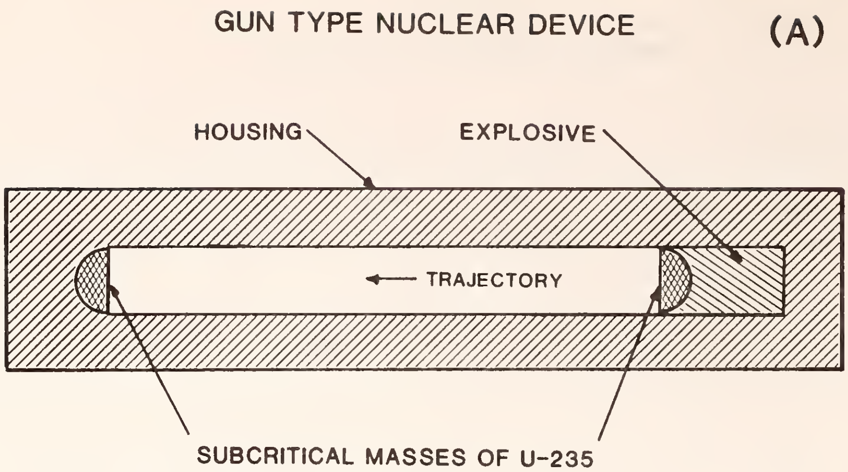
## ACCIDENTS INVOLVING NUCLEAR WEAPONS

A nuclear weapon consists of a housing, high explosives, and a sub-critical assembly of fissile materials (Figure VII-1). The fissile nuclides are either $^{235}U$ or $^{239}Pu$, although $^{233}U$ could also be used if available in sufficient mass. The term fissile means that a nuclide can be made to fission by neutrons of any energy. The term fissionable means that the nuclide can be made to fission by neutrons having the right energy; for example, $^{238}U$ will fission only if bombarded by high energy neutrons. The term fusionable refers to light nuclides that can undergo fusion, principally deuterium ($H^2$), tritium ($H^3$), and lithium (Li). Fusionable materials are components of thermonuclear weapons (hydrogen bombs).

The purpose of the high explosive in a weapon is to bring the fissile material together rapidly so that a nuclear detonation can be induced. Two basic types of assemblies have been used. The gun type consists of two sub-critical masses of highly enriched $^{235}U$ brought together in a gun-type housing (Figure VII-1A). The nuclear weapon dropped over Hiroshima, Japan in 1945 was a gun-type device. The other basic assembly uses a mass of fissile material in a sub-critical geometry surrounded by high explosives. Detonation of the chemical high explosive compresses or implodes the fissile material into a critical assembly causing a nuclear detonation (Figure VII-1B). The implosion technique was developed for fission of $^{239}Pu$ because of the presence of $^{240}Pu$ which has a high spontaneous fission rate. The required assembly velocities were not possible with the gun-type device. Both the Trinity device and the nuclear weapon detonated over Nagasaki were implosion-type devices, using $^{239}Pu$ as the fissile fuel. By 1948, highly enriched $^{235}U$ was also used in the more efficient implosion devices (Mark et al. 1983).

A thermonuclear device uses various combinations of fissile, fissionable, and fusionable materials in a complex assembly. Fission of the fissile materials by standard techniques serves as the trigger that provides the special conditions necessary for the thermonuclear reaction to occur and to release energy and high energy neutrons that boost the reaction by inducing fission in the $^{238}U$. The physical conditions required to achieve a nuclear detonation by the implosion technique are extremely restrictive.

Safety has been an important consideration since the beginning of development, testing, and use of nuclear weapons. Intricate arming sequences were a part of the safety procedures designed into the weapons. Only for testing or use in combat has a nuclear weapon been armed so that a nuclear detonation could occur. An unplanned nuclear detonation is highly unlikely as a consequence of sabotage or accident with a nuclear weapon. In some nuclear weapons, several dozen detonators must be fired in a precisely timed sequence. Any detonation that is single point in origin or random in nature will detonate all or most of the high explosive, but does not produce a nuclear yield. Instead, the chemical explosion would disperse the fissile materials. Because of the pyrophoric nature of metallic plutonium and uranium, a very fine aerosol of plutonium oxide and uranium oxide is formed. This aerosol is of respirable size and it is the principal health hazard from an accidental detonation of high explosives in an armed nuclear weapon. The immediate hazard is from inhalation of the plutonium oxides and, to a lesser extent, ingestion of plutonium oxides. The maximum permissible body burden of $^{239}Pu$ is 40 nCi and the maximum permissible lung burden of insoluble plutonium is 16 nCi (about 0.25 micrograms). Because nuclear weapons contain kilogram quantities of $^{239}Pu$, aerosolization of only a few percent could result in a significant inhalation hazard. The alpha specific activity of weapons grade $^{239}Pu$ (0.061 Ci/g) is ~ 30,000 times the alpha specific activity of enriched $^{235}U$ (~ $2 \times 10^{-6}$ Ci/g); therefore, the hazard from aerosolization of $^{235}U$ is less. Aerosolization of fissionable $^{238}U$ is even less hazardous because its specific activity is only $3.33 \times 10^{-7}$ Ci/g.



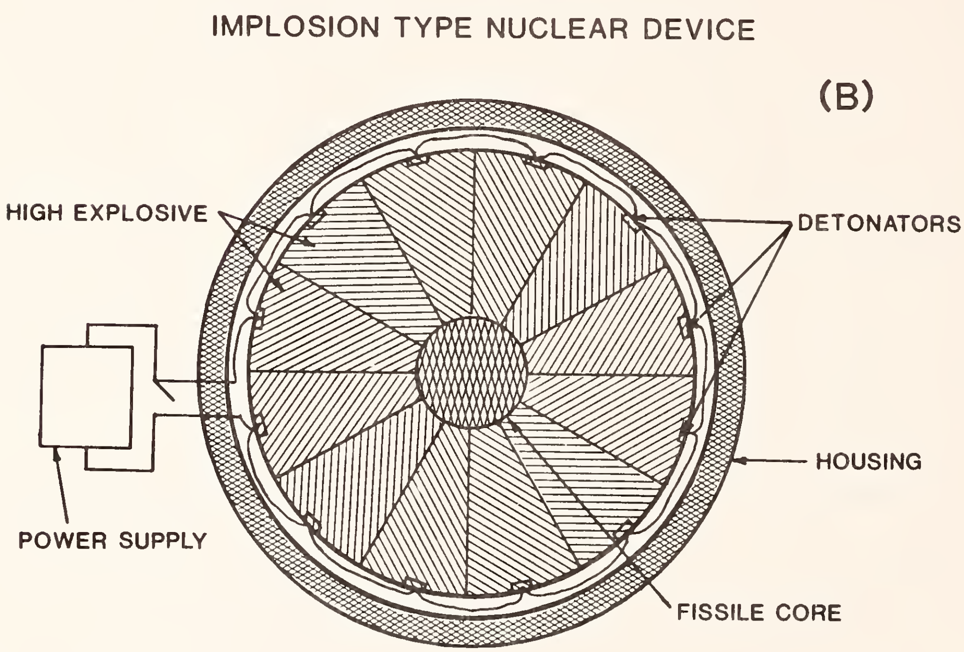




Figure VII-1. Schematic diagrams of nuclear weapons. Figure 1A shows the gun type assembly and Figure 1B illustrates the principle of the implosion system (adapted from Glasstone and Dolan 1977).

Previous Nuclear Weapons Accidents

"Broken Arrow" is a term used to designate an accident involving nuclear weapons or nuclear weapon components (DOD 1981). The following lines are reproduced from this report.

Description of an Accident

An "accident involving nuclear weapons" is defined as

An unexpected event involving nuclear weapons or nuclear weapons components that results in any of the following:

> Accidental or unauthorized launching, firing, or use, by U. S. forces or supported allied forces, of a nuclear-capable weapon system which could create the risk of an outbreak of war.
>
> Nuclear detonation.
>
> Non-nuclear detonation or burning of a nuclear weapon or radioactive weapon component, including a fully assembled nuclear weapon, an unassembled nuclear weapon, or a radioactive nuclear weapon component.
>
> Radioactive contamination.
>
> Seizure, theft, or loss of a nuclear weapon or radioactive nuclear weapon component, including jettisoning.
>
> Public hazard, actual or implied.

Several "Broken Arrows" have occurred involving aircraft, missile silos, transportation of weapons, accidents at storage or assembly plants, and in submarines. The exact number cannot be obtained from unclassified sources. In 19B1, the United States Department of Defense released a report entitled "Narrative Summaries of Accidents Involving U. S. Nuclear Weapons 1950 - 19B0 (DOD 19B1). This report lists 27 aircraft accidents, 1 submarine accident, 3 missile silo accidents, and 1 accident at a storage igloo on Medina Base, Texas - all involving nuclear weapons (Table VII-1). In addition, the USS Thresher sank in the Atlantic Ocean on April 10, 1963, presumably carrying nuclear weapons. The event in the spring of 196B, listed "at sea", is attributed to the loss of the USS Scorpion, a Skipjack class nuclear attack submarine that sank near the Azores in May 196B. Lewis (1967) reported another accident that may have occurred in 1957 when a B-47 jet-powered aircraft carrying nuclear weapons crashed and burned on takeoff at the United States Air Force Base near Sidi Slimane, Morocco. The conventional high explosive was reported to have detonated "spraying pulverized plutonium downwind, however the contamination was restricted to the air base so that no outsiders were affected". The resulting cleanup used personnel from both the Navy and Air Force, and this experience led to establishment of the Joint Nuclear Accident Coordinating Center. Its initials were JNACC and was generally referred to as Janac. Other "Broken Arrows" may have occurred and various sources report the maximum number to be 95. Two accidents that resulted in dispersed plutonium occurred near Palomares, Spain and Thule, Greenland.

Palomares, Spain

On January 17, 1966, a B-52 carrying four nuclear weapons collided with a KC-135 tanker aircraft during refueling and both aircraft crashed near Palomares, Spain. The B-52 was one of about 600 B-52s that were part of the United States' Strategic Air Command's manned bomber alert. From 1959 to 196B, the Strategic Air Command maintained about half of the available B-52s in the air at all times. They carried nuclear weapons and their globe girdling flights required mid-air refueling. From 1959 to 196B, about 750,000 mid-air refuelings were performed. The incident over Palomares was one of a very small number of mid-air refuelings that went awry.

The four crewmen of the KC-135 were killed in the explosion, but four of seven crewmen from the B-52 survived. Debris from the two aircraft, including the four nuclear weapons, fell in and around the village of Palomares (Figure VII-2). One nuclear weapon landed intact in a dry bed of the Almanzora River and was recovered intact. The second and third nuclear weapons landed with sufficient force to detonate the high explosive and thereby dispersed the plutonium. Plutonium oxide particles dispersed to nearby areas resulted in contamination as shown in Figure VII-3. The fourth nuclear weapon fell into the Mediterranean Sea about 5-1/2 miles off shore. A Spanish fisherman saw a large object descend by parachute following the mid-air collision and his observation was crucial in the final recovery.

Table VII-1

Broken Arrow Incidents Reported by the U. S. Department of Defense

| Date | Location | Accident Type | Contamination | High Explosive Detonation | Capsule Installed |
|---|---|---|---|---|---|
| 02/13/50 | E. Pacific near British Colombia | Weapon jettisoned into ocean from aircraft | No | Yes | No |
| 04/11/50 | Manzano Base, Alb. NM | Aircraft crash | No | No | No |
| 07/13/50 | Near Lebanon, Ohio | Aircraft crash | No | Yes | No |
| 08/05/50 | Travis AFB, Calif. | Aircraft crashed on emergency landing | No | Yes | No |
| 11/10/50 | Ocean | Weapon jettisoned from aircraft | No | Yes | No |
| 03/10/56 | Mediterranean Sea | Lost aircraft carrying 2 capsules only | No | --- | --- |
| 07/27/56 | Overseas Base | Aircraft crashed into storage igloo | No | No | No |
| 05/22/57 | Kirtland AFB, Alb. NM | Weapon dropped from aircraft | Slight | Yes | No |
| 07/28/57 | Atlantic Ocean | Two weapons jettisoned from aircraft | No | No | No |
| 10/11/57 | Homestead AFB, Florida | Aircraft crashed on takeoff | No | Yes | No |
| 01/31/58 | Overseas Base | Aircraft landing gear failed on takeoff | Yes | No | Yes |
| 02/05/58 | Off coast near Savannah River, Georgia | Weapon jettisoned | No | No | No |
| 03/11/58 | 6.5 mi East of Florence, South Carolina | Weapon accidently jettisoned | No | Yes | No |
| 11/04/58 | Dyess AFB, Texas | Aircraft crashed after takeoff | Yes | Yes | Yes |
| 11/26/58 | Chennault AFB, Louisiana | Aircraft caught fire on ground | Yes | No | Yes |
| 01/18/59 | Pacific Base | Aircraft caught fire on ground | No | No | No |
| 07/06/59 | Barksdale AFB, Louisiana | Aircraft crashed on takeoff | Yes | No | Yes |

Table VII-1 (Continued)

Broken Arrow Incidents Reported by the U. S. Department of Defense

| Date | Location | Accident Type | Contamination | High Explosive Detonation | Capsule Installed |
|---|---|---|---|---|---|
| 09/25/59 | Off Whidbey Island, Washington | Aircraft ditched in Puget Sound | No | No | No |
| 10/15/59 | Near Hardinsberg, Kentucky | Refueling collision and crash | No | No | No |
| 06/07/60 | McGuire AFB, New Jersey | BOMARC missile fire and explosion | Yes | No | Yes |
| 01/24/61 | Goldsboro, North Carolina | Aircraft broke up in flight (2 weapons) | No | No | Yes |
| 03/14/61 | Yuba City, California | Aircraft ran out of fuel and crashed | No | No | Yes |
| 11/13/63 | Medina Base, Texas | 123,000 lbs explosion of H.E. components | Slight | Yes | --- |
| 01/13/64 | 17 mi SW Cumberland, Maryland | Aircraft broke up in flight (2 weapons) | No | No | Yes |
| 12/05/64 | Ellsworth AFB, S. Dakota | LGM 30B Minute Man I fell over | No | No | Yes |
| 12/08/64 | Grissom AFB, Indiana | Aircraft skidded on takoff and burned | Yes | No | Yes |
| 10/05/65 | Wright-Patterson AFB, Ohio | Aircraft caught fire while refueling on runway | Yes | No | No |
| 12/05/65 | At sea, Pacific | Aircraft rolled off a U. S. Carrier | No | No | Yes |
| 01/17/66 | Palomares, Spain | Aircraft refueling collision and crash | Extreme | Yes (2 of 4) | Yes |
| 01/21/68 | 7 mi SW of Thule AFB, Greenland | Aircraft crashed and burned | Extensive | Yes | Yes |
| May/68 | At sea off Azores | Lost submarine | ---------------Classified | -------------- | |
| 09/19/80 | Damascus, Arkansas | Titan II ICBM silo fire | No | No | Yes |

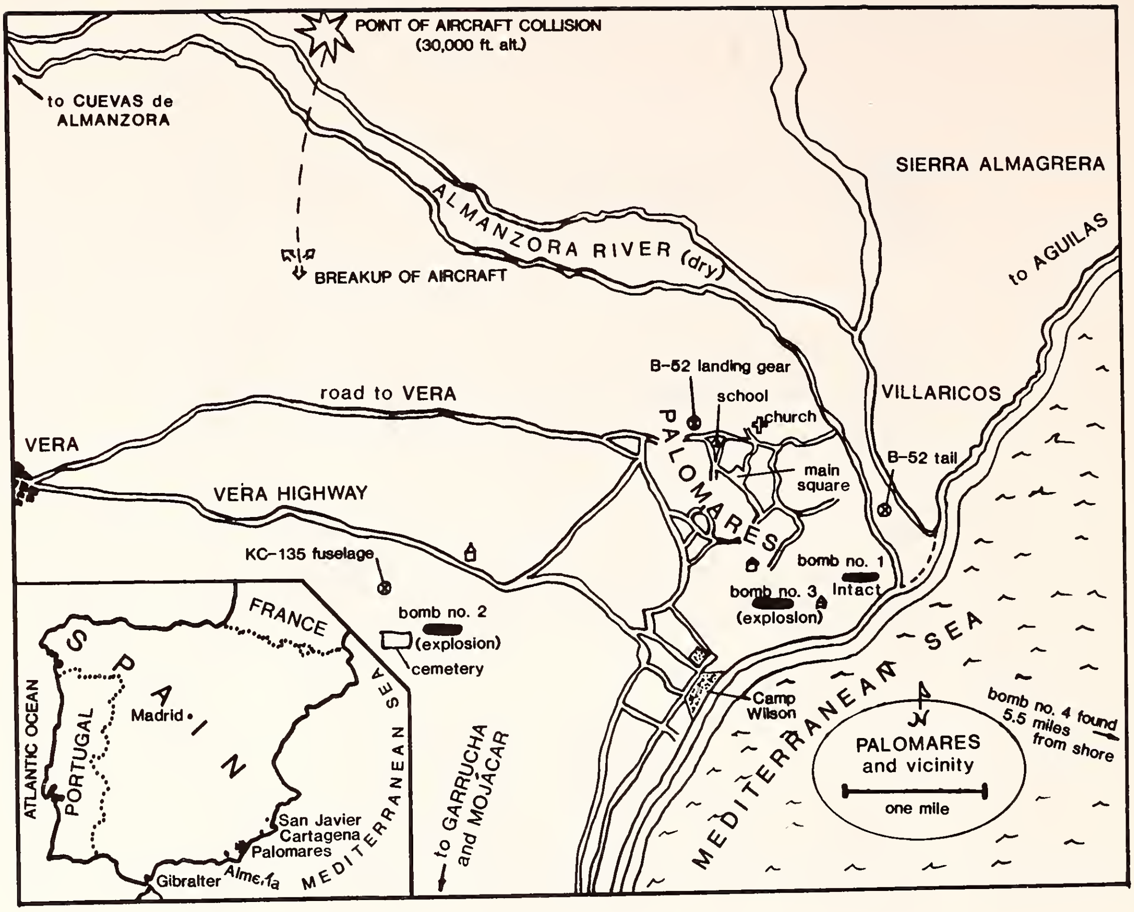



Figure VII-2. Map of Palomares showing positions where three nuclear weapons impacted on land. The fourth nuclear weapon parachuted into the Mediterranean Sea about 5-1/2 miles from shore. Location of Palomares in Spain is shown in the inset (adapted from Szulc 1967).

People living in Palomares are mainly farmers and tomatoes are their major crop. Fortunately, winds blew the plutonium away from the village proper. It was also fortunate that a member of the Spanish Guardia Civil quarantined the fields and prevented people from entering the most contaminated areas. This was done to prevent disturbance of the aircraft debris since the Guardia Civil representative did not suspect radioactive contamination.

Representatives of the Spanish Junta Energia Nuclear, the United States Foreign Service, and the United States Military forces began decontaminating the affected areas almost immediately. Scientists from the weapons laboratories advised on techniques and suggested levels of radioactivity that required action. No official standards for action following soil contamination existed. After lengthy negotiations and study of the maps showing levels of plutonium contamination, an agreement on remedial action was reached. In the final agreement, all crops were stripped from the fields and destroyed where readings above 5 $\mu$g plutonium/m$^2$ were observed. All areas where readings were between 5 and 500 $\mu$g/m$^2$ were plowed to a depth of at least 10 inches. Areas with readings over 500 $\mu$g/m$^2$ were stripped of top soil. Top soil was removed from 5-1/2 acres and vegetation was removed from 600 acres which was subsequently plowed. Areas too rough to plow, but contaminated to the extent of 50 $\mu$g/m$^2$ or higher, were worked by hand to turn the surface contamination into the soil. Decontamination consisted of removing

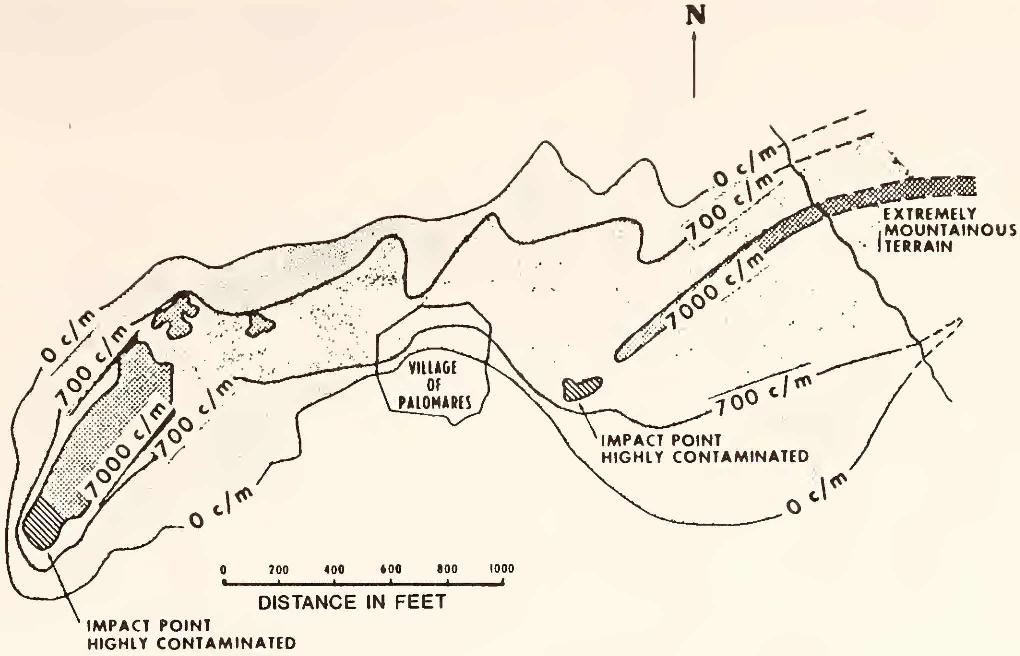



Figure VII-3. Map of isocontamination contours (c/m, alpha counts per minute) near Palomares resulting from the high explosive (chemical) detonations of two of four nuclear weapons in 1966 (Langham 1968).

tomato vines and other vegetation and scraping off a thin layer of topsoil. This was followed by plowing. About 800 American military personnel worked in the decontamination effort and searched for two months for the fourth bomb thought to be in the Mediterranean Sea. Altogether, 265.7 acres of farmland were "made almost surgically clean" (Morris 1966).

When it became obvious that the fourth nuclear weapon was in the Mediterreanean Sea, the United States Navy established Task Force 65 to attempt to locate it. With the help of submersible research vessels, the nuclear weapon was finally located, lost, and eventually relocated. Finally, on April 7, 1966, 80 days after the mid-air collision, the nuclear weapon was raised from a depth of 2650 feet and secured aboard a naval vessel for return to the United States. Viewing by the press was also permitted.

World press coverage and Soviet propaganda focused on the search for the missing nuclear weapon while the decontamination effort proceeded with little publicity. The contaminated material from Palomares was placed into about 4,600 separate 55-gal steel drums, loaded aboard a ship, and transported to the United States for final disposal at the Savannah River Project near Aiken, South Carolina.

Total cost to the United States, not including the lost aircraft and the two destroyed weapons, was about 100 million dollars. About 80 million was spent in decontaminating the land, in medical exams of residents of Palomares, and in retrieval of the weapon that sank in the sea. The remainder was for miscellaneous costs and reparations to Spanish citizens who were unable to harvest and sell their crops, fish, and shrimp due to plutonium contamination and temporary concern for any produce or seafood from the Palomares area.

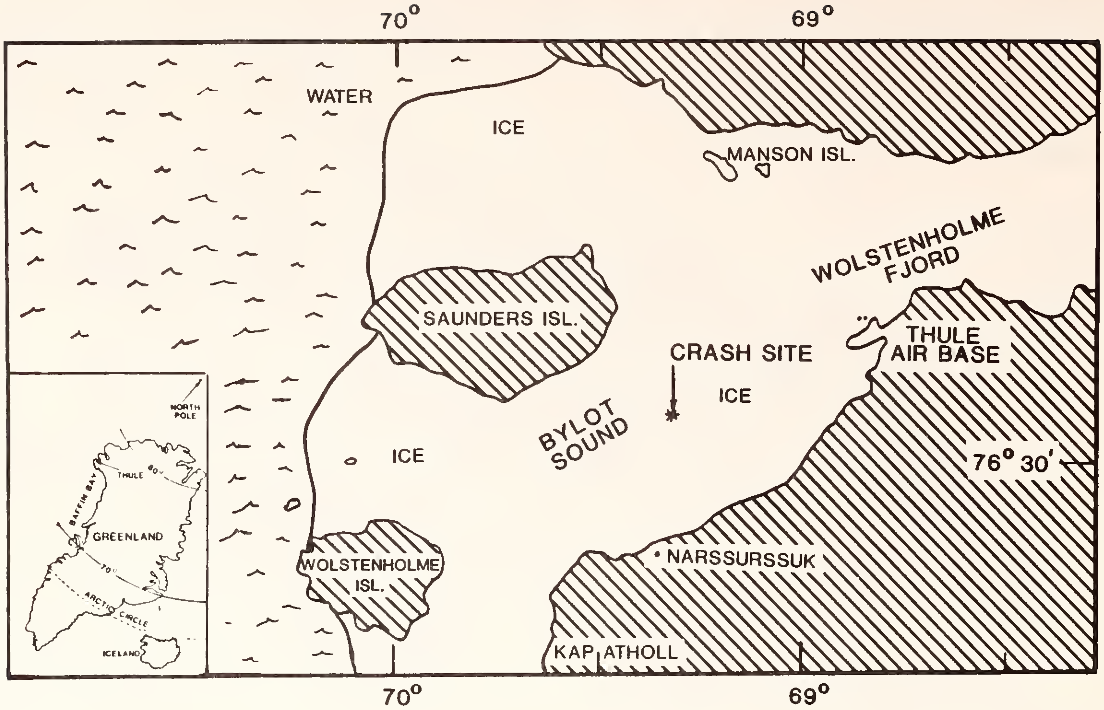



Figure VII-4. Map of the area around Thule Air Force Base showing location of the B-52 crash site on the sea ice of Bylot Sound. Location of Thule in Greenland is shown in the inset (adapted from Langham 1970).

As a result of the incident at Palomares, the Spanish Government denied permission to refuel airplanes over Spanish territory. With the departure of the American servicemen and reporters, Palomares returned to normal and after a few months, produce from the area was again accepted in markets. The tomato fields have been expanded in recent years and the Spanish Junta Energia Nuclear continues to monitor produce for plutonium and conducts extensive soil sampling efforts in the formerly contaminated area.

In retrospect, the insistence on secrecy by the United States and Spanish governments concerning this accident on foreign soil involving private citizens of the host country may have been a mistake, but it probably did not affect safety. However, this policy was endorsed by the Spanish Government who feared local panic if the events were known. Admission from the United States Diplomatic Corps that a nuclear weapon had been lost did not occur until about 6 weeks after the incident. Presidential authority to United States Ambassador Duke to reveal the complete story was granted over objections from the Joint Chiefs of Staff (Szulc 1967).

Thule, Greenland

On January 21, 1968, a B-52 aircraft carrying four thermonuclear weapons and following a northbound course over Baffin Bay developed an onboard fire. The pilot requested permission to make an emergency landing at the United States Air Force Base located on Danish territory at Thule, Greenland. Permission was granted and the aircraft changed course towards Thule. However, as the aircraft approached Thule from the south, the rapidly growing fire forced a bailout order from the pilot. Six of the seven crewmembers survived. The abandoned aircraft circled to the northwest and crashed on sea ice in Bylot Bay about 7-1/2 miles from the end of the runway (Figure VII-4). The B-52 hit the ice at a shallow angle at a speed in excess of 500 nautical

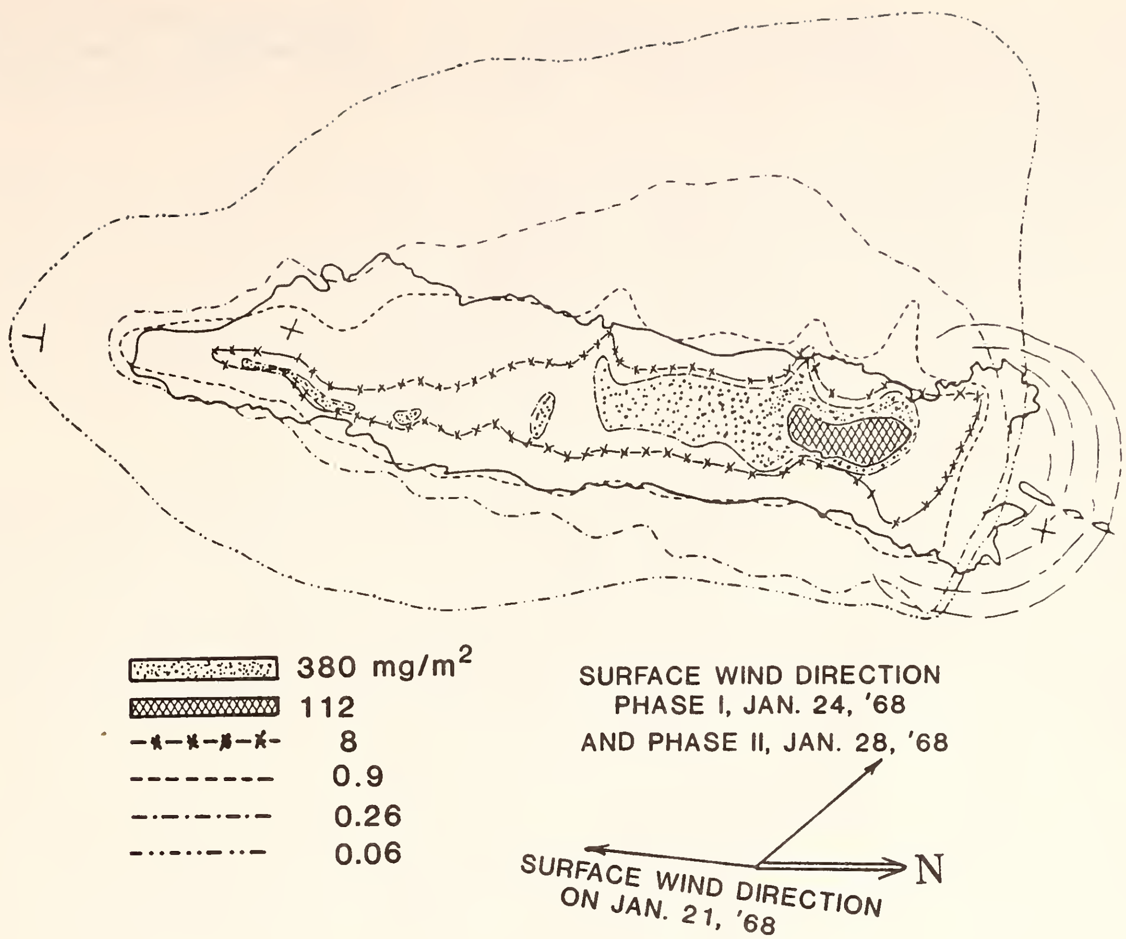



Figure VII-5. Map of the isocontamination contours (mg of Pu/$m^2$) on the sea ice of Bylot Sound, Greenland, resulting from the B-52 crash and high explosive (chemical) detonation of four nuclear weapons on January 21, 1968. The solid line outlines the area of snow and ice blackened by the burned fuel (adapted from Langham 1970).

miles per hour. The aircraft gross weight was about 410,000 pounds of which about 225,000 pounds was fuel. The high explosive components of the four nuclear weapons detonated, blowing the plutonium into the burning fuel. Burning fuel, aircraft debris, and the plutonium oxide particles were spread along the surface ice which was covered with about 10 inches of snow. Soon after the accident the fire was extinguished, leaving a blackened refrozen crust on the snow pack. This area was 300-400 feet wide and approximately 2200 feet long and contained about 3150 g of plutonium-239 (Langham 1970). The ice was shattered at the impact point but quickly refroze in the -40° temperature. Figure VII-5 is a map of the contaminated area showing levels of contamination and contour values. A cloud of smoke and debris containing an estimated 1-5 Ci of plutonium had drifted west-southwest and deposited uncertain amounts of plutonium on the sea ice and landscape (Langham 1970).

In contrast to the Palomares incident two years earlier, the United States Air Force quickly released details of the incident. The cleanup operation (Project Crested Ice) was promptly and effectively conducted by United States Military Personnel with representatives of the Danish Government overseeing the effort. Over a two-month period, about 237,000 cubic feet of

contaminated ice, snow, water, and crash debris were removed. The volume of snow and ice was reduced by melting and evaporation and the concentrated debris was placed in 67 separate 25,000 gallon tanks and shipped to the Savannah River Project radioactive waste repository near Aiken, South Carolina.

No significant contamination was found either on the land masses or in the marine environment after ecological studies were completed after the sea ice melted in the summer of 1968. Bottom sediments contain 25-30 Ci of $^{239}Pu$. Beyond 40 km from the impact point, environmental plutonium levels were not significantly above background fallout levels (Aarkrog 1977). By 1974, the plutonium levels in marine animals were lower by an order of magnitude. No significant increase of plutonium in fish, seabirds, and marine mammals was detected in either of the surveys in 1970 or 1974 (Aarkrog 1977). To date, the plutonium release has been confined to the bottom fauna and people have not been at risk.

Summary of Palomares and Thule Incidents

The Thule, Greenland and Palomares, Spain "Broken Arrow" incidents are the only accidents involving nuclear weapons that resulted in widespread plutonium contamination. Current nuclear weapons designs use more insensitive high explosives so that the potential for chemical detonation in case of traumatic accidents is reduced. In 1968, as a result of the Palomares and Thule incidents and in part due to deployment of intercontinental ballistic missles and Polaris submarines, the United States discontinued the manned-bomber airborne alert that carried nuclear weapons. This eliminated about 300 aircraft in the air at all times and greatly reduced the probability of accidents similar to the Palomares or Thule incidents.

Early nuclear weapons designs used in-flight-insertable capsules of fissile material. Therefore, when not a combat or test situation, if the weapon was subjected to extreme trauma, the capsule was not inserted and the resultant chemical detonation did not aerosolize plutonium. With the development of sealed units, the potential for aerosolization of plutonium slightly increased in case of extreme trauma. Missile silo fires and transportation accidents are presently the most likely situations that can cause future "Broken Arrows". As long as relatively large numbers of nuclear weapons are transported, deployed, refurbished and stored, a potential exists that "Broken Arrow" incidents will happen. However, because the United States no longer maintains a manned-bomber airborne alert, the probability of Broken Arrows similar to Palomares or Thule is smaller.

As a result of the nuclear weapons accident in Spain, a potential exists that citizens of Palomares will request compensation from the United States. If the U.S. Environmental Protection Agency adopts a soil standard for plutonium such as the proposed screening level of 0.2 $\mu Ci/m^2$ (top 1-cm of soil = 27 pCi/g), then people living near Palomares would have a basis for seeking compensation. Langham (1968) reported that areas with contamination up to 500 $\mu g/m^2$ were only plowed. This plutonium would have to be evenly distributed throughout a layer at least 175 cm thick to meet the proposed soil standard.

Figure VII-6 illustrates the actinide soil standard proposed by the U.S. Environmental Protection Agency (1977) including health risk implications based on assumptions of deposition and uptake in people. The projected health effects via the ingestion pathway are due to cancer mortality and genetic risk. For practical reasons in implementating the proposed standard, the U.S. Environmental Protection Agency derived a numerical value of 0.2 $\mu Ci/m^2$ as the screening level for soil samples collected to a depth of 1 cm and for particles less than 2 mm diameter. Assuming typical resuspension rates, the predicted airborne concentration above contaminated soil is 2.6 femto $Ci/m^3$ ($2.6 \times 10^{-15}$ $Ci/m^3$). This airborne concentration is assumed to result in an average dose of 3 mrad/year to bone or 1 mrad to lung tissues. The calculated risk would be one cancer per million people per year increase over the normal rate.

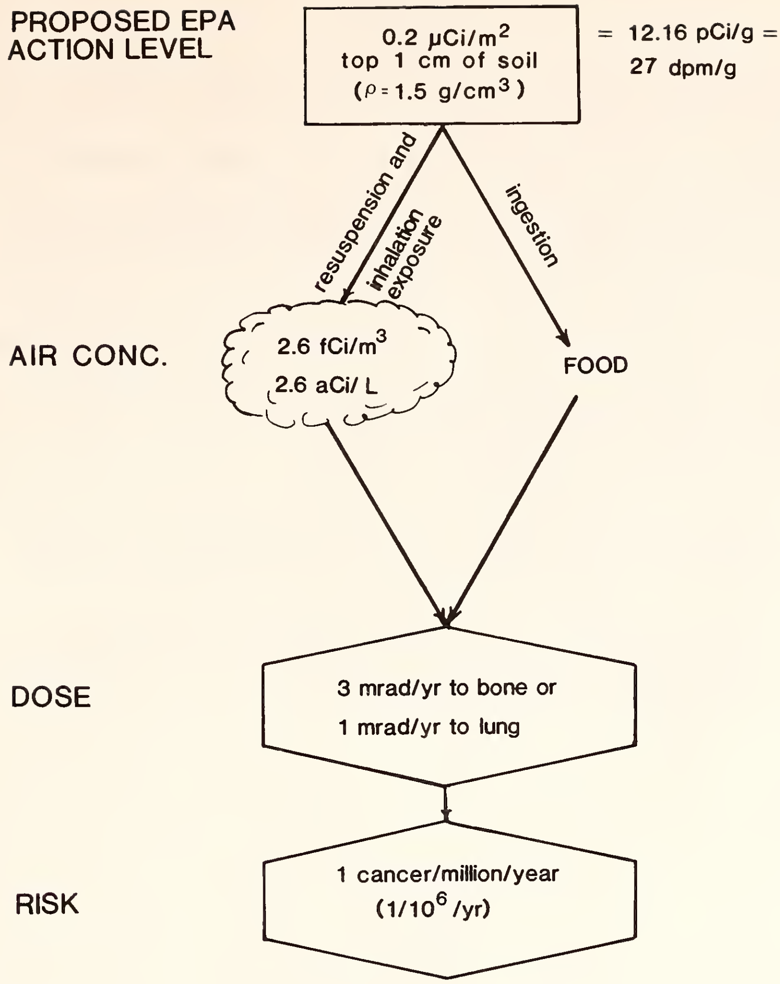



Figure VII-6. Illustration showing the derivation of the proposed United States Environmental Protection Agency's actinide soil concentration guidelines. The calculated air concentration is estimated to result in a radiation dose to bone or lung that would increase a person's risk of developing cancer by $1/10^6$/year.

Litigation damage claims could be filed by members of the United States Military that participated in the cleanups at Palomares and Thule, even though no one received a maximum permissible body burden. Odland et al. (1968) reported that of nearly 1700 participants at Palomares, about 20% had a systemic body burden of $^{239}Pu$ detectable by urinalyses. Of these, only 26 were in the range of 7-70% of one permissible body burden.

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## SECTION VIII
## SUMMARY

Concerns for health risks from exposures to ionizing radiation are a part of all nuclear weapons industry operations. They led to the development of current radiation protection philosophy and exposure control standards for radiation workers and the public; they provided the impetuous for moving nuclear weapons tests underground; they stimulated costly efforts to decontaminate large areas of soil where releases of radioactivity had occurred; and they now lead to significant numbers of lawsuits throughout the United States involving workers and the public. The Code of Federal Regulations specifies that radiation workers should not accumulate whole-body doses at a rate exceeding 5 rem per year. Thus, lifetime occupational exposures (assuming 50 years of employment) should not exceed 250 rem. Permissible doses to most individual organs are three times those for the whole body. Exposures to members of the public are specified to be no more than 1/10 of those to workers. Regardless of these regulations, industry management should be aware that a simple statement of compliance with exposure standards is not a sufficient legal defense against personal injury claims. Most claims are now resulting from worker exposures less than 100 rem and exposures to members of the public less than 10 rem.

Our ability to make quantitative health risk projections for external radiation exposures less than 250 rem is mainly derived from human epidemiology studies. These include studies of Japanese atomic bomb survivors and medical patients exposed to X-rays during treatment for various diseases. Other studies of nuclear industry workers involve much lower radiation exposures, so low that they are not likely to result in quantitative estimates of risk. However, they may be used to estimate maximum values of risk factors that would be useful in projecting upper limits of risk for individuals exposed to low radiation doses. This use of low dose information, obtainable from epidemiology studies, should be developed further.

Controversies among scientists with regard to predicting health risks from low level radiation exposures result from the statistical uncertainty of events that occur with a low probability. Radiation-induced cancers have only been demonstrated to occur in populations exposed to more than about 50 rem. However, scientists generally agree that the probabilities of developing radiation-induced cancers below 50 rem of exposure can be estimated by extrapolating information from higher exposed populations downward into the low dose region. This requires a mathematical model. To date, linear, linear-quadratic, and quadratic equations have been proposed for this purpose in combination with either an absolute or relative risk calculation. Thus, six different low dose predictions of risk can be made from the same set of experimental data. The highest and lowest values differ by a factor of 60 in the most recent National Research Council report by the Committee on the Biological Effects of Ionizing Radiation. These uncertainties are of sufficient magnitude to impact significantly upon decisions made in adversary litigations. They will only be resolved by onging epidemiology studies (i.e., studies of Japanese atomic bomb survivors) that are likely to continue for 20 years or more. These studies should be given priority. Other studies of nuclear industry workers (i.e., Handford worker studies) should also be continued, although they are likely to provide only upper limits of radiation cancer risks in the low dose region.

Studies using laboratory animals have been most useful in evaluating radiation risks from types of exposure for which no epidemiological information is available. This includes predicting the risks of health effects from most internally deposited radionuclides and of genetic effects for all types of radiation exposure. In general, studies using laboratory animals have not been used to make direct quantitative predictions of radiation risks for humans, but they have been used to determine the relative potencies of different types of radiation exposures. For example, animal studies have enabled scientists to know that particles of plutonium deposited in the lungs

are not significantly more carcinogenic than uniformly distributed plutonium in lungs; that plutonium deposited in bone is 10 to 20 times more carcinogenic than an equal amount of radium; that lung cancer risks from inhaled particles containing alpha- and beta-emitting radioactivity are similar to risks for people who inhaled radon or were exposed to external low-LET radiations, respectively.

Studies in laboratory animals have provided the only direct evidence of the genetic effects of low to intermediate levels of radiation and they have been used to develop quantitative risk factors. These risks are rarely the subject of current litigations and this is surprising because the genetic risk due to radiation exposure is thought to be similar in magnitude to the cancer risk. For example, the risk of causing genetic defects is 5 to 65 per million live births per rem, and the total cancer risk is thought to be 10 to 600 cases per million persons per rem. Since several thousand cancer cases are currently being alleged to have been caused by radiation in ongoing litigations, a similar number of alleged radiation-induced birth defects might be expected. More genetic injury litigations may be expected in future years if public awareness and concern increase and if competent legal and scientific experts become available to argue such claims.

A potentially troublesome aspect of radiation injury litigation may develop around the contention that current exposure control standards do not account for simultaneous exposures to multiple toxic agents. At the present time, scientific knowledge on radiation health effects is inadequate for accurately determining the risks to people who are also exposed to cigarette smoke, fibers, and carcinogenic chemicals. Many occupations involve complex exposure situations and it may well be argued that there is an insufficient basis for judging their exposure risks. Because an almost infinite number of possible exposure combinations exist, new general mathematical models are needed for evaluating risks from mixtures of toxic agents. This information cannot come from studies in people so that research support will be needed for laboratory animal studies with selected combinations of carcinogenic agents conducted at levels appropriate to worker exposure conditions.

Most litigations that have been initiated by people who were exposed to radiation from nuclear weapons testing involve external whole-body doses of less than 20 rem. These are similar in magnitude to natural background and medical radiation exposures and are not expected to cause measureable health effects based upon current scientific knowledge. However, in some cases, radiation doses were caused by internally deposited radioactivity which may be difficult to evaluate after many years have passed.

Testimony supporting plaintiffs' claims often relies on epidemiologic studies or statistical analyses that lack scientific rigor. Many of these studies do not provide estimates of radiation doses to the exposed and control populations, and some have even been based upon health effects as reported in surveys that are not verified by medical records. Such testimony may be given weight in radiation injury litigations because of a lack of understanding of its highly technical nature and because personal sympathies generally lie with plaintiffs who are afflicted by serious diseases. To be effective, arguments by the defense must be clear and logical to a degree that is difficult to achieve without technical expertise and extensive preparation.

Specifically with regard to radiation health effects, research that has been most important in litigations includes the following:

A. Human epidemiology studies of populations that have well documented radiation exposures and large numbers of individuals exposed to less than 100 rem to critical tissues;
B. Laboratory studies that provide dosimetry information for constructing mathematical models to estimate doses from internally deposited radioactivity in people;

C. Laboratory studies that identified critical organs at risk and provided estimates of the magnitudes of the health risks due to exposures for which human epidemiologic information is not available;

D. Cancer registry data bases that provide long-term histories of disease incidences in specific populations throughout the United States;

E. Statistical analyses of radiation dose-effect information to develop models through which risks measured at exposure levels above 100 rem can be used to predict risks at lower exposure levels;

F. Published studies that provide detailed statistical evaluations and reviews of controversial radiation epidemiology studies or health risk models appearing in the scientific literature.

Litigations involving damage to property have resulted from serious as well as insignificant levels of radioactive contamination. Residual radioactivity from weapons tests conducted in the Marshall Islands was determined to represent a potential health risk to area residents causing them to live in other areas for many years. About 300 Marshallese who lived on the northeastern atolls during the Pacific nuclear weapons tests received external and internal radiation exposures that caused measureable health effects to their skin and thyroids. In contrast, radioactivity released from the Rocky Flats facility northwest of Denver, Colorado has been determined not to be a significant health risk to nearby residents. However, a few studies have claimed to detect Rocky Flats plutonium in area residents and increased incidences of cancers in the local population. These observations have not been verified in separate studies or in reviews of the original publications. Nonetheless, concern for plutonium on land bordering the Rocky Flats facility led to a major litigation even though it was estimated that the residual plutonium could not increase the exposure of a person living on the land by more than 1% of the natural background level.

Accidents in which nuclear weapons were involved in airplane crashes have also led to contamination of land with plutonium. One crash near Polamares, Spain left residual plutonium contamination that is still being studied after 20 years. A second crash near Thule, Greenland occurred on a frozen bay and contaminated a large area of snow and ice. The surface radioactivity was removed and the remainder was dispersed by ocean currents over a large area on the bottom of the bay when the ice thawed.

Attempts to clean up large areas of land contaminated with radioactivity have met with varied success. In the Marshall Islands, cleanup efforts only removed about one-half of the residual radioactivity, and the resulting reduction of health risks to area residents is hardly significant in proportion to the efforts expended. Although cleanup of the plutonium released off-site from the Rocky Flats facility is probably not warranted at this time, if efficient cleanup methods had been applied to the original spill, a great deal of public concern and litigation could have been avoided. Cleanup of plutonium near Palomares still needs further evaluation, but that near Thule appears to represent an insignificant risk to area residents.

With regard to the management of incidents involving radioactive contamination of soil, research that has been most important in litigations and cleanup operations includes the following:

A. Studies that provided our overall knowledge concerning the movement of radioactivity in soil;

B. Research on resuspension of radioactivity from soil into air;

C. Studies of food chain pathways for describing the movement of radioactivity through the environment to man;

D. Measurements of the levels of radioactivity in the environment and in the tissues of people who live nearby in order to characterize important contamination incidents;

E. Health risk assessment studies that develop relationships between levels of radioactivity in the environment and the probabilities for causing human health effect.

In light of previous experiences associated with nuclear weapons industry operations and litigations that occurred because of normal operations and accidents that led to radiation exposures of people, the following new research needs are apparent. First, radioactivity released to the environment leading to contamination of large areas of soil will require that criteria be established for judging the need for cleanup. Currently, these decisions are voluntary, but they may initiate lengthy litigations through which <u>de facto</u> criteria by nonscientific legislative or judicial means are established.

Second, research is needed in developing effective methods for removing radioactivity deposited on surface soil. Current methods have relied on large earth moving equipment, but experience indicates that this approach leads more to mixing of the radioactivity through deep soil layers than removal. Large expenditures have resulted in small reductions in health risks to people living near contaminated sites. Ideally, cleanup approaches would be able to remove the top layers of different types of surface soils before disturbing deeper layers. Improved cleanup techniques will be needed to manage future accidents whether they involve large or small areas, and real or perceived health risks.

Third, continued research on health risks from low-level exposures to ionizing radiation is needed to aid in resolving litigations and public concerns for nuclear industry operations in general. Long-term epidemiology studies of atomic bomb survivors, medical patients, and radiation workers must be continued along with selected studies in laboratory animals to determine if current radiation standards are applicable to workers who are exposed to complex mixtures of toxic substances; to determine whether the relative or absolute cancer risk model is more appropriate for attributable risk calculations; and to develop verifiable methods for extrapolating the results of studies using laboratory animals to human risk assessment in evaluating exposures for which no human epidemiologic information is available.

Finally, new efforts are needed to demonstrate the validity of mathematical models that are used to predict radiation doses to people from radioactivity released to the environment. Many models are currently available for this purpose, but their ranges of uncertainty and applicability to specific exposure situations has not been demonstrated. Thus, model calculations for estimating radiation exposures to people involved in litigations may be seriously challenged or shown to be highly arbitrary.

Absolute risk: Expression of excess risk due to exposure as the arithmetic difference between the risk among those exposed and that obtained in the absence of exposure.

Alpha particle: A charged particle emitted from a nucleus having a mass and charge equal to those of helium nucleus: two protons and two neutrons.

Attenuation: Process by which a beam of radiation is reduced in intensity when passing through material--combination of absorption and scattering processes, leading to a decrease in flux density of beam when projected through matter.

Average life (mean life): Average of lives of individual atoms of a radioactive substance; 1.443 times radioactive half-life.

BEAR Committee: Advisory Committee on the Biological Effects of Atomic Radiation (precursor of BEIR Committee).

BEIR Committee: Advisory Committee on the Biological Effects of Ionizing Radiations.

Beta particle: Charged particle emitted from the nucleus of an atom, with mass and charge equal to those of an electron.

Bremsstrahlung: Secondary photon radiation produced by deceleration of charged particles passing through matter.

Chamber, ionization: An instrument designed to measure quantity of ionizing radiation in terms of electric charge associated with ions produced within a defined volume.

Curie (abbr., Ci): Unit of activity = $3.7 \times 10^{10}$ nuclear transformations per second. Common fractions are:

- Megacurie: One million curies (abbr., MCi).
- Microcurie: One-millionth of a curie (abbr., μCi).
- Millicurie: One-thousandth of a curie (abbr., mCi).
- Nanocurie: One-billionth of a curie (abbr., nCi).
- Picocurie: One-millionth of a microcurie (abbr., pCi).

Decay, radioactive: Disintegration of the nucleus of an unstable nuclide by spontaneous emission of charged particles, photons, or both.

Decay product (synonym, daughter): A nuclide resulting from radioactive disintegration of a radionuclide, formed either directly or as a result of successive transformations in a radioactive series; may be either radioactive or stable.

Dose: A general term denoting the quantity of radiation or energy absorbed; for special purposes, must be qualified; if unqualified, refer to absorbed dose.

- Absorbed dose: The energy imparted to matter by ionizing radiation per unit mass of irradiated material at the point of interest; unit of absorbed dose is the rad.
- Cumulative dose: Total dose resulting from repeated exposure to radiation.
- Dose equivalent (abbr., DE): Quantity that expresses all kinds of radiation on a common scale for calculating the effective absorbed dose; defined as the product of the adsorbed dose in rads and modifying factors; unit of DE is the rem.
- Permissible dose: The dose of radiation that may be received by an individual within a specified period with expectation of no substantially harmful result.
- Threshold dose: The minimal absorbed dose that will produce a detectable degree of any given effect.
- Doubling dose: The amount of radiation needed to double the natural incidence of a genetic or somatic anomaly.
- Dose fractionation: A method of administering radiation in which relatively small doses are given daily or at longer intervals.

Dose protraction: A method of administering radiation in which it is delivered continuously over a relatively long period of low dose rate.

Dose rate: Absorbed dose delivered per unit time.

Electron volt (abbr., eV): A unit of energy = 1.6 X $10^{-12}$ ergs = 1.6 X $10^{-19}$ J; 1 eV is equivalent to the energy gained by an electron in passing through a potential difference of 1 V. 1 keV = 1,000 eV; 1 MeV = 1,000,000 eV.

Exposure: A measure of the ionization produced in air by X or gamma radiation; the sum of electric charges on all ions of one sign produced in air when all electrons liberated by photons in a volume of air are completely stopped in air, divided by the mass of the air in the volume; a unit of exposure in air is the roentgen (abbr., R).

Fissile nuclide: A nuclide that can be made to fission by neutrons of any energy.

Fission, nuclear: A nuclear transformation characterized by the splitting of a nucleus into at least two other nuclei and the release of a relatively large amount of energy.

Fission products: Elements or compounds resulting from fission.

Fission yield: The percentage of fissions leading to a particular nuclide.

Fissionable nuclide: A nuclide that can be made to fission by neutrons having a specific energy.

Fusion, nuclear: Act of coalescing of two or more nuclei.

Fusionable nuclide: Light nuclides that can undergo fusion, principally duterium, tritium, and lithium.

Gamma ray: Short-wavelength electromagnetic radiation of nuclear origin (range of energy, 10 keV to 9 MeV).

Gray (abbr., Gy): Unit of absorbed dose of radiation = 1 J/kg = 100 rads.

Half-life, biologic: Time required for the body to eliminate half an administered dose of any substance by regular processes of elimination; approximately the same for both stable and radioactive isotopes of a particular element.

Half-life, effective: Time required for a radioactive element in an animal body to be diminished by 50% as a result of the combined action of radioactive decay and biologic elimination = [(biologic half-life) (radioactive half-life)]/[(biologic half-life) + (radioactive half-life)].

Half-life, radioactive: Time required for a radioactive substance to lose 50% of its activity by decay.

Incidence: The rate of occurrence of a disease within a specified period; usually expressed in number of cases per million per year.

Ion: Atomic particle, atom, or chemical radical bearing an electric charge, either negative or positive.

Ionization: The process by which a neutral atom or molecule acquires a positive or negative charge.

Ionization density: Number of ion pairs per unit volume.

Ionization path (track): The trail of ion pairs produced by ionizing radiation in its passage through matter.

Primary ionization: In collision theory, the ionization produced by primary particles, as contrasted with "total ionization," which includes the "secondary ionization" produced by delta rays.

Secondary ionization: Ionization produced by delta rays.

Isotopes: Nuclides having the same number of protons in their nuclei, and hence the same atomic number, but differing in the number of neutrons, and therefore in the mass number; chemical properties of isotopes of a particular element are almost identical; term should not be used as a synonym for "nuclide."

Kerma (Kinetic Energy Released in Material): A unit of quantity that represents the kinetic energy transferred to charged particles by the uncharged particles per unit mass of the irradiated medium.

Latent period: Period of seeming inactivity between time of exposure of tissue to an injurious agent and response.

Linear energy transfer (abbr., LET): Average amount of energy lost per unit of particle spur-track length.

Low LET: Radiation characteristic of electrons, X-rays, and gamma rays.

High LET: Radiation characteristic of protons and fast neutrons. Average LET is specified to even out the effect of a particle that is slowing down near the end of its path and to allow for the fact that secondary particles from photon or fast-neutron beams are not all of the same energy.

Linear hypothesis: The hypothesis that excess risk is proportional to dose.

Medical exposure: Exposure to ionizing radiation in the course of diagnostic or therapeutic procedures; as used in this report, includes:

1. Diagnostic radiology (e.g., X-rays).
2. Exposure to radioisotopes in nuclear medicine (e.g., iodine-131 in thyroid treatment).
3. Therapeutic radiation (e.g., cobalt treatment for cancer).
4. Dental exposure.

Micrometer (symbol, μm): Unit of length = $10^{-16}$ m.

Morbidity: 1. The condition of being diseased.

2. The incidence, or prevalence, of illness in any sample.

Neoplasm: Any new and abnormal growth, such as a tumor; "neoplastic disease" refers to any disease that forms tumors, whether malignant or benign.

Nonstochastic: Describes effects whose severity is a function of dose; for these, a threshold may occur; some nonstochastic somatic effects are cataract induction, nonmalignant damage to skin, hematologic deficiencies, and impairment of fertility.

Nuclide: A species of atom characterized by the constitution of its nucleus, which is specified by the number of protons (Z), number of neutrons (N), and energy content or, alternatively, by the atomic number (Z), mass number (A = N + Z), and atomic mass; to be regarded as a distinct nuclide, an atom must be capable of existing for a measurable time; thus, nuclear isomers are separate nuclides, whereas promptly decaying excited nuclear states and unstable intermediates in nuclear reactions are not.

Person-rem (synonym, man-rem): Unit of population exposure obtained by summing individual dose-equivalent values for all people in the population. Thus, the number of person-rems contributed by 1 person exposed to 100 rems is equal to that contributed by 100,000 people each exposed to 1 mrem.

Quality factor (abbr., QF): The LET-dependent factor by which absorbed doses are multiplied to obtain (for radiation-protection purposes) a quantity that expresses the effectiveness of an absorbed dose on a common scale for all kinds of ionizing radiation.

Rad: Unit of absorbed dose of radiation = 0.01 J/kg = 100 ergs/g.

Radiation: 1. The emission of propagation of energy through space or through matter in the form of waves, such as electromagnetic waves, sound waves, or elastic waves.

2. The energy propagated through space or through matter as waves; "radiation" or "radiant energy," when unqualified, usually refers to electromagnetic radiation; commonly classified by frequency--Hertzian, infrared, visible, ultraviolet, X, and gamma ray.

3. Corpuscular emission, such as alpha and beta radiation, or rays of mixed or unknown type, such as cosmic radiation.

Background radiation: Radiation arising from radioactive material other than that under consideration; background radiation due to cosmic rays and natural radioactivity is always present; there may also be background radiation due to the presence of radioactive substances in building material, etc.

External radiation: Radiation from a source outside the body.

Internal radiation: Radiation from a source within the body (as a result of deposition of radionuclides in tissue).

Ionizing radiation: Any electromagnetic or particulate radiation capable of producing ions, directly or indirectly, in its passage through matter.

Secondary radiation: Radiation resulting from absorption or other radiation in matter; may be either electromagnetic or particulate.

Radioactivity: The property of some nuclides of spontaneously emitting particles or gamma radiation or of emitting X radiation after orbital electron capture or of undergoing spontaneous fission.

Radioisotopes: A radioactive atomic species of an element with which it shares almost identical chemical properties.

Radionuclide: A radioactive species of an atom characterized by the constitution of its nucleus; in nuclear medicine, an atomic species emitting ionizing radiation and capable of existing for a measurable time, so that it may be used to image organs and tissues.

Relative biologic effectiveness (abbr., RBE): A factor used to compare the biologic effectiveness of absorbed radiation doses (i.e., rads) due to different types of ionizing radiation; more specifically, the experimentally determined ratio of an absorbed dose of a radiation in question to the absorbed dose of a reference radiation required to produce an identical biologic effect in a particular experimental organism or tissue; the ratio of rems to rads; if 1 rad of fast neutrons equaled in lethality 3.2 rads of kilovolt-peak (kVp) X-rays, the RBE of the fast neutrons would be 3.2

Relative risk: Expression of risk due to exposure as the ratio of the risk among the exposed to that obtaining in the absence of exposure.

Rem: A unit of dose equivalent = absorbed dose (in rads) times quality factor times distribution factor times any other necessary modifying factors; represents quantity of radiation that is equivalent--in biologic damage of a specified sort--to 1 rad of 250-kVp X-rays.

Roentgen (abbr., R): A unit of exposure = $2.58 \times 10^{-4}$ coulomb/kg of air.

Sievert (abbr., Sv): Unit of radiation dose equivalent = 100 rems.

Stochastic: Describes effects whose probability of occurrence in an exposed population (rather than severity in an affected individual) is a direct function of dose; these effects are commonly regarded as having no threshold; hereditary effects are regarded as being stochastic; some somatic effects, especially carcinogenesis, are regarded as being stochastic.

Working level (abbr., WL): Any combination of radon daughters in 1 liter of air that will result in the ultimate emission of $1.3 \times 10^{5}$ MeV of potential alpha energy.

Working-level month (abbr., WLM): Exposure resulting from inhalation of air with a concentration of 1 WL of radon daughters for 170 working hours.

X-ray: Penetrating electromagnetic radiation whose wavelength is shorter than that of visible light; usually produced by bombarding a metallic target with fast electrons in a high vacuum; in nuclear reactions, it is customary to refer to photons originating in the nucleus as gamma rays, and those originating in the extranuclear part of the atom as X-rays; sometimes called roentgen rays, after their discoverer, W. C. Roentgen.

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